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EVOLUTIONARY MECHANISM OF SCIENTIFIC PROGRESS:

BEYOND KUHN'S SCIENTIFIC REVOLUTIONS

BY

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DEFENSA DE TESIS

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We must believe that to discover accurately the cause of the most essential facts is the function of the science of nature, and that blessedness for us … lies in … knowing too that what occurs in several ways or is capable of being otherwise has no place here.

Epicurus, *Letter to Herodotus*

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Contents

I. Before the structure

The philosophy of science is a part of epistemology which is concerned with the foundations of science. According to the definition of Encyclopedia Britannica the philosophy of science is "the study, from a philosophical perspective, of the elements of scientific inquiry" (Kitcher 2018). In other words, philosophy of science is concerned with problem such as what is science, by what methods knowledge is acquired, what is the relation of the knowledge with reality and truth, and what is the purpose of scientific activity. A central problem of the philosophy of science is the demarcation between science and other human activities.

A major distinction of scientific theories is their universality. While in common knowledge, on each particular subject, different opinions and disagreements could exist, the scientific world view is shared by the scientific community among virtually all people and cultures. Scientific truth is considered the highest standard of truth. This begs the questions: what makes scientific knowledge different from other types of knowledge? How is such knowledge produced? And why science exists in general?

These questions are as old as science itself. The universality of science seems to imply that there are fundamental logical principles that govern how science is conducted and how scientific knowledge is accumulated and verified. The existence of such principles, that are shared among all rational beings, is the most straightforward way to ensure that each individual independently reaches the same conclusions presented the same information. Not surprisingly this was the line of thought of most of the philosophers of science from Aristotle to Popper.

1. Origins: causes

The first comprehensive theory of scientific inquiry was developed by Aristotle. He defined science as the study of the causes of the things (Aristotle, n.d.). He distinguished four types of causes – *material, formal, efficient, and final.* The material cause is the set of the physical properties of the object. Matter by itself has certain properties but it is not yet an object, it only has the potentiality to become one. The formal cause is the design or the structure of the object. The formal cause is what makes one object different from another although they are made of the same material. The efficient cause is the agent which brings the object into being. The final cause is the purpose of the object. The Aristotelian view is derived from biology, in the sense that it considers everything as an organism. For example, in a red blood cell the inorganic and organic molecules which make up its body are the material cause of the cell; in the cell the different molecules combine to make its membrane and organelles which give the cell its structure and are the formal cause of the cell; the efficient cause is the process of red cell production in the bone marrow; and ultimately the purpose of the ref blood cell is to carry oxygen from the lungs to the tissues. Aristotle's philosophy is teleological in the sense that everything exists for a purpose.

With this view of the causes Aristotle categorized the different types of knowledge (Aristotle, n.d.). The most basic knowledge is empirical knowledge which is derived from sensory experience (material cause). Aristotle divided the sciences into two categories: practical (*techne*) and theoretical (*episteme*). The purpose of practical science is to study the formal causes in order to learn how to produce useful objects. On the contrary, theoretical science is concerned with the study of the efficient or intermediate causes and its primary purpose is explanation rather than utility. Finally, philosophy is the study of the final or primary causes.

2. Classical understanding: laws of nature

The development of modern science after the Renaissance inevitably changed the perception of the philosophy of science. As a sequel to the work of Galileo, Descartes and others a new picture emerged of science as a *study of phenomena and the relations between the phenomena* (Descartes 1637). Modern science dispensed with the formal and final causes and concentrated on the immediate causes of the phenomena. The main premise is that Nature displays regularity, which regularity could be expressed in the form of *natural laws*. Science's aim was to uncover these laws.

This effort culminated with the development of the scientific method, which was originally formulated by Francis Bacon (Bacon 1620). The original proposition of Bacon was that truth about nature can be discovered by experimentation. This was a radical departure from ancient science which was predominantly theoretical, where the theories were based on observations of naturally occurring phenomena. In its modern formulation, the scientific method incorporated the empiricism of Bacon with the theoretical approach of the ancient science with the falsification approach developed in modern times. It consists of several steps which are continuously repeated. First, careful observation of the phenomena and experimentation (including computer simulations) lead to the formulation of a hypothesis; the hypothesis is tested by further targeted experimentation; based on the results of the hypothesis is rejected or not and further hypotheses are formulated. There are two important features of the method. First, *empiricism*: unlike ancient science, which was based on observation of naturally occurring phenomena, in modern science experimentation is made the core of the sciences; nothing that cannot be empirically tested is science. Second, *hypothesis testing*: a hypothesis is only good until the first time it contradicts observations. In fact, the results of *hypothesis testing* are stated in the negative i.e. given the available data the hypothesis cannot be rejected.

3. Modern philosophy of science: logical principles

In the modern philosophy of science, the empiricism of the scientific method developed into the *logical positivism movement that sought to reduce all knowledge to logical or empirical foundations* (Morris 1937). The main tenet of logical positivism is *verification*, i.e. that a statement is meaningful only if it could be determined to be true or false by a logical derivation from a set of formal (logical or mathematical) statements or empirical facts. The initial momentum of the movement eventually stalled because multiple problems were pointed out with the principle of verification. Validation is based on the validity of a generalization of empirical observations, but the generalization itself can never be strictly verified. Such generalizations are inductive and, as Hume argued, no amount of confirmation can prove an inductive argument, because it is always possible that the very next observation contradicts the theory (Hume 1748). Moreover, the observation itself is problematic as all observations are paradigm dependent, thus in a sense the results of experiments are already products of interpretation.

Popper recognized and tried to amend the problem of validation (Popper 1934). He utilized the asymmetry between validation and falsification, in other words although a theory cannot be validated by any amount of testing and confirmation, it can be falsified by a single test that contradicts the predictions of the theory. Thus, Popper elevated what is called *hypothesis falsification* to be the demarcation between science and nonscience. First, if a theory does not allow for testing, it cannot in principle be verified or refuted, and then, it is just a matter of opinion and it is not science. Second, a theory cannot in principle be verified or confirmed, it can only be refuted. Thus, according to Popper science proceeds through *conjectures and refutations* (Popper 1962). In other words, when faced with a problem, scientists state a hypothesis. The hypothesis is tested and if it is rejected a new hypothesis is formed. If not rejected, the hypothesis is used as *modus operandi* until evidence occurs rejecting it.

Falsification faces the same objections as validation with respect to interpretation of experiments. The accuracy of experiments can always be challenged, and the theory can always be patched to account for rogue experiments. Thus, various philosophers, among which Lakatos (Lakatos 1970), argued that this naïve falsification does not work. Lakatos in turn proposed 'sophisticated' falsification procedure which he thought resolved this problem.

Another problem with the naïve falsification is the absurd conclusion that a theory that has passed a myriad of tests is as good as a theory that has been hardy tested. In order to deal with this problem, some philosophers of science have proposed Bayesian verification (Howson and Urbach 2005). This is based on the Bayes' theorem for conditional probability which dictates how to revise predictions in the light of relevant new evidence (Routledge 2018). From the point of view of Bayes' theorem, each test that does not reject the theory constitutes new relevant evidence and the conditional probability for the theory to be correct increases. This makes well-established theories more reliable than new entrants.

Nevertheless, even assuming that an incorrect theory can be falsified, still the problem remains of choosing between two theories that give similar predictions and neither can be strictly falsified. The traditional rationalists, such as Popper, thus make a number of additional assumptions based on a belief on the structure of the relation between nature and the mental representation of it. There are two possible stances on the relation between nature and the mental representation of it: idealism and realism. *Idealism* is the doctrine that we cannot assume that reality exists since all that we are aware of is the mental picture. Instead, the mind "is the ultimate foundation of all reality, or even exhaustive of reality" (Guyer and Horstmann 2018). *Realism* on the contrary presupposes that reality exists independent of the observer and it is the basis of all experience.

However, realists differ on the relationship between representation and reality (Perez Ransanz 1999). *External realism* assumes that the objects of the representation are the product of the application of absolute categories on experience, as proposed by Kant (Kant 1781). Thus, the objects are independent of any mental framework. A strong version of the external realism is the *scientific realism* which assumes that the objects of the representations correspond to things-in-themselves. Thus, scientific knowledge is absolute and independent of any local perspective, and the scientific theories converge to the actual description of nature, i.e. objects-in-themselves and laws of nature. Scientific realism has been the dominant belief in the sciences and the philosophy of science from Galileo and Descartes to Popper.

Scientific realism is fundamental to the principal tenets of modern philosophy of science. The assumption is that successive theories encompass previous theories and they asymptotically approach reality (Popper 1934). Therefore, competing theories can be compared based on how much closer they are to reality. This means that there are purely logical criteria to guide the development of science which do not change although the content of scientific theories changes. They are also universal, independent of historical or sociological factors. Furthermore, since theories include previous theories and have ever increasing empirical base, scientific development is continuous and progressive.

These notions were challenged in the *historical turn* in the philosophy of science which was pioneered by authors such as Kuhn, Lakatos, Feyerabend, and Laudan (Nickles 2017). Kuhn's *The Structure of Scientific Revolutions* is the first and the most influential work of this movement (Kuhn 1962). The main tenet of the historical movement is that the history of science is a valuable source for the development of models of scientific change (Perez Ransanz 1999). Moreover, historical evidence suggests that the scientific development is neither continuous nor cumulative but exhibits discontinuous jumps. In addition to the historical perspective, another important aspect of the historical turn is the relationship between representation and reality. This new philosophy of science espouses *internal realism* or *representationalism* which assumes that the objects of the representation do not exist outside of conceptual frameworks (Putnam 1981, 1987). There is also not a unique way to organize experience, i.e. different frameworks could be consistent with experience. As a consequence, since the relationship between the framework and the world-in-itself is not one of identity, there is not an objective way to compare scientific theories. Therefore, there are no rational criteria that govern scientific change in the sense of Popper.

4. Where to next

In the *Structure*, Kuhn challenged some of the fundamental preconceptions of the classical philosophy of science and introduced a very different conceptual framework of the development of science. In response, the philosophers of science contended with various aspects of Kuhn's theory, such as the concept of paradigm itself, Kuhn's insistence on the incommensurability of the paradigms, the apparently irrational process of the transition between paradigms, and Kuhn's relativism i.e. that the there is no reality beyond the paradigm and the concept of truth is paradigm dependent. The reason Kuhn's view is vulnerable to criticism is that it is based on generalizations of observed historical developments of science. However, Kuhn never elaborated an underlying mechanism for developing paradigms which is implied in and the product of which are all these historical exemplars.

Thus, the question posed in this thesis is: *Is there an underlying mechanism behind the scientific progress as described by Kuhn in the Structure? Can this mechanism explain Kuhn's observations? Can it help reinterpret and possibly resolve objections raised by Kuhn's critics?*

In order to answer these questions we turn to recent developments in mathematics, biology, physics, economics, and informatics which have been converging from different angles on the problem of what has become known as *complex systems* (Holland 1995). In complex systems interactions between simple parts of a system give rise to the complex collective behaviors of the system. Complexity means that the properties of the system cannot be easily derived from the properties of the parts. A complex system is typically represented as a population of interacting agents. The interactions between the agents can be represented by a network. Such systems exhibit the appearance of spontaneous order which is exemplified by the emergence of new properties (Holland 1999). The complexity is not designed but it is self-organized (Prigogine 1984; Kauffman 1993).

From the vantage point of these developments, the hypothesis we propose in this thesis is that *the mechanism behind scientific progress is evolution by natural selection of worldviews. The worldview is selected for its predictive power. A successful worldview has more predictive power and, in effect, enhances the survivability of the societies that adopt it. The worldview itself is an information structure that can be represented by the mathematical concept of a graph. The graph consists of concepts in its vertices and the connections between them represented by edges. All mental processes can be represented as operations on the graph.*

The principal objectives of this study are as follows:

Overview of Kuhn's model of scientific revolutions

Summarize Kuhn's original model and introduce all key concepts. Follow up with a summary of the main objections to the model and outline Kuhn's responses and the amendments he made to his theory. Introduce some of the alternative models of the development of scientific knowledge.

Introduce the network model of knowledge acquisition

Knowledge can be represented by an associative network. The concepts make the vertices of the network and the relationships between the concepts the edges of the network. The edges are directed to indicate a logical relation between the concepts; they are also weighted to indicate the strength of the relation. The network evolves from an initial state by adding or removing vertices and edges. The rules that govern the addition of vertices and edges to the network determine the structure or topology of the network. By a paradigm then we mean an associative network of concepts representing a worldview. The initial network consists of a few fundamental concepts and relations derived from experience. Then it grows by adding other empirically-derived or abstract concepts to it and the corresponding relationships between them. All mental processes can be represented as operations on this graph, such as additions or deletion of vertices and edges. In particular, true statements can be represented with paths on the graph.

Develop the concept of evolution of information

Evolution is the only known process that can spontaneously construct complexity starting from simple elements. The key elements of the evolutionary process are replication, mutation, and selection. Replication adds new entities. Mutation produces new variants of the next generation of entities. Selection removes the variants that are not well adapted to the environment. Evolution is by no means confined to the domain of biology. Whenever information reproduces, with variation, there is evolution. In that sense DNA, which encodes the genetic information of all life forms, is just one type of information message. Errors in the information transfer produce new type of information. Selection emerges when some messages reproduce faster than others. With that in mind we can think of scientific progress as evolution of paradigms or worldviews.

The knowledge network is an information structure. It replicates by imitation or copying as individuals learn it from others through personal interaction, formal education, or written sources. The replication is, however, not exact, each new individual can incorporate a somewhat different version of the paradigm. In addition, each individual can make conscious changes to the network in the process of subsequent learning, investigation, or logical analysis. Therefore, the paradigm mutates during duplication. If the new paradigm is superior, i.e. it gives better predictions of reality, it will give the individuals who adopt is higher survival rates and better quality of life. A successful paradigm will motivate other individuals to adopt it. This is the process of selection.

Demonstrate that evolution of knowledge networks explains Kuhn's principal observations about the scientific progress

We can accommodate Kuhn's principal observations comfortably within the concept of a network evolution. For example, a period of normal science is a coherent growth of the network when new vertices and new edges are added to the existing network and/or vertices/edges are adjusted. In this sense, the growth of knowledge during a period of normal science is cumulative. An anomaly appears when a vertex or a connection is invalidated. Due to the connectivity of the network, a whole subnet or a cluster around the anomaly is also gradually invalidated. This is the period of crisis. Revolutionary science then is the process of replacing the invalidated subnet or cluster with a new set of vertices and connections between them.

Interpret and resolve the polemic issues in Kuhn's view of the scientific from the point of view of network evolution

This model also can help us resolve the issues with some of Kuhn's concepts. When a cluster in the network is invalidated, it is gradually replaced with a new one. Incommensurability arises because the new and the old cluster do not share vertices or connections, thus they literally cannot be compared. Furthermore, since truth is making statements consistent with the network, it has no meaning outside of the network or paradigm. Thus, the choice between the old and new subnets cannot be made based on the concept of truth, because there is no such concept that functions outside of either paradigm. Nevertheless, the choice between paradigms is rational. Paradigms are built to make predictions about reality. The individuals and groups chose the paradigm with the larger predictive power in order to improve their evolutionary fitness. Rational beings will adopt superior paradigms.

Kuhn's view of scientific development is built on induction, by generalizing on a number of historical exemplars of paradigm shifts. However, the historical perspective does not provide un underlying mechanism for this process. In contrast, the approach of this thesis is analytic. It proposes a general model for knowledge representation and revolution and explains the phenomenology based on this model. The result is an original look at Kuhn's now classical concepts and claims that introduces in the philosophy of science some of the latest scientific developments such as network science, evolutionary dynamics, and complex systems.

In that regard, the author is very well positioned to develop this topic. One of the major problems with the philosophy of science is that it has been practiced mostly by professional philosophers with limited knowledge of the domain sciences and little experience in the actual practice of the sciences. With time, this has produced a disconnect between the sciences and the philosophy of science to the extent that modern scientific developments have very little impact on the philosophy of science, presumably because philosophers are not aware of them or do not understand them sufficiently well. In contrast, the author of this thesis is a scientist with truly interdisciplinary preparation. He holds advanced degrees in physics, computer science, and economics. He has published tens of articles in high impact journals, mostly in the area of physics but also in finance and evolutionary biology.

The *interpretation of Kuhn's theory of the scientific revolutions through the vantage point of evolution of a network of concepts thus is original and contemporary* and it could be a very fruitful area or research with possibility of potentially high impact findings.

II. The Structure

Kuhn's contribution to the philosophy of science came about in an unconventional way. He was trained as a theoretical physicist in Harvard. Later he specialized in the history of science, teaching courses on the history of science at Harvard and then Berkeley, where he was eventually appointed as a professor of history of science. Thus, not surprisingly, he introduced the historical aspect in the philosophy of science. His first major work, on the Copernican revolution, was a work on the history of science (Kuhn 1957). His magnum opus, *The Structure of Scientific Revolutions* (Kuhn 1962) was probably meant to be a book on history of science as well, except that the level of generalization and abstraction of the historical examples, which Kuhn achieved, qualified it as philosophy. In addition to the historical aspect, however, as a trained physicist, Kuhn was well acquainted with the day-to-day work of the scientist and understood intimately the intellectual struggle to conceptualize new worldviews around the times one scientific theory superseded another. This vantage point enabled him to give a coherent and comprehensive description of scientific progress, which in turn made his work so influential.

In order to develop further Kuhn's theory, we first need introduce Kuhn's principal ideas as presented in the *Structure* (Kuhn 1962):

1. Paradigm

Central to Kuhn's description of the scientific process is the concept of a *paradigm*. Here he defines paradigm as "some accepted examples of actual scientific practice" that "provide models from which spring particular coherent traditions of scientific research" (Kuhn 1962, p.10). In this definition Kuhn invokes the dictionary definition of the word paradigm which is used as a pattern, model, or template. However, he wanted to avoid the burden of preexistent meaning which these other terms have. For that reason, he picked the little-then-used word paradigm. This practice is common among philosophers, for example Kant coined many neologisms in order to avoid the intuitive association of commonly used terms with preexistent meanings that are not his own (Kant 1781). The word paradigm itself is not a neologism, it comes from Greek and means to show side by side. It had been used previously in the sense of a template for something or an exemplar.

The theory of scientific development proposed by Kuhn revolves around the concept of paradigm. According to him the history of science can be viewed as a succession of paradigms each dominating for a certain amount of time after which it is replaced by another paradigm. Kuhn states that the initial state of any field of knowledge is the pre-paradigm state when there is no dominant model. At this stage of development there could be multiple models existing simultaneously which, however, are not compatible with each other and do not possess enough explanatory power to displace the competing models. Typically, each model could only explain part of the phenomenology in a satisfactory manner. Thus, the scientific activity in the pre-paradigm state mostly concentrated on fundamentals, arguing the advantages of one model over the others. Because of the focus on fundamentals, the scientific production during this period is low.

This all changes when a model appears that promises to explain the available phenomenology. This model is initially developed by an individual or a group of individuals. If the paradigm is more successful than competing paradigms in solving problems in that particular domain, over time other practitioners either convert to the paradigm or leave the field, by which process the paradigm is established as dominant and competing paradigms disappear. The community subscribing to the paradigm is the core of a domain science. Under a dominant paradigm the scientific community is involved in solving problems within the scope of the paradigm, which activity Kuhn labels normal science. Most of the scientific work is done during the periods of normal science, because there are no arguments about fundamentals and all scientists work in the same direction. These periods are characterized by continuous expansion of knowledge and high productivity.

Of particular interest is the relation between a paradigm and a worldview which Kuhn makes in Chapter X of the *Structure* entitled *Revolutions as Changes of World View*. This is where Kuhn's view of scientific progress really starts deviating from the established *status quo* and his originality starts to shine. Also, this is there the controversy starts. According to Kuhn, changes in the paradigm modify how the world is perceived and that people themselves are changed by the paradigm. He says that "when paradigms change, the world itself changes with them" (Kuhn 1962, p.111). Kuhn states that scientist subscribing to different paradigms "pursue their research in different worlds" (*ibid*. p.120) and that "during revolution scientists see new and different thinks when looking with familiar instruments in places they have looked before" (*ibid*. p.111). In other words, the world is perceived through a paradigm and there can be no scientific activity outside of a paradigm. Individuals that have different sets of concepts cannot effectively communicate with each other. This is the essence of Kuhn's concept of incommensurability.

2. Normal science

Most of the scientific work is done during the state of *normal science*. Under this state, the productivity of the scientists is the highest, because there are no quarrels over fundamentals; instead, the whole scientific community is focused on elaborating the paradigm. The work within the paradigm is directed at explaining existing phenomenology in terms of the paradigm and on making new predictions and discovering new phenomena using the paradigm. In a sense, this is an *extensive expansion* of scientific knowledge: new knowledge is accumulated by exploring the dimensions already defined by the paradigm.

Kuhn's attitude towards normal science appears to be somewhat negative. First, he likens normal science to "puzzle-solving", not because it is a trivial activity, but because the scientist already knows that there is a solution, no matter how technically difficult it is to obtain it. Kuhn says that the "paradigm is a criterion for choosing problems, that, while the paradigm is taken for granted, can be assumed to have solutions" (Kuhn 1962, p.37). In other words, from the point of view of the paradigm a scientist can say which problems belong to the domain science, i.e. can be solved within it, and which cannot.

Then, Kuhn also says that paradigm science does violence on the history of the science. As in a war, the victor writes the history, so in paradigm science all knowledge is reinterpreted through the prism of the paradigm itself. Textbooks are continuously rewritten to show the most up-to-date understanding of paradigm science and, as a result, the tortuous process of formalizing the paradigm is lost. Also, previous paradigms are only used to illustrate the buildup towards the paradigm, not always in historically correct context. As the authors of textbooks interpret the pre-paradigm developments through the prism of the paradigm, they subconsciously revise the history to make the development look continuous. Even researchers themselves in their later works reinterpret their earlier findings in the view of their present understanding, again making it look continuous.

3. Anomalies

Eventually, normal science reaches the limitations of the paradigm. Since the paradigm is only a model, eventually nature may not comply with the predictions of the model. These instances Kuhn calls *anomalies*. A few anomalies, however, do not stop normal science. If the anomalies are few and far between, they will go unnoticed for a while. The results will be customarily interpreted using the paradigm and any deviations would be labeled as errors of measurement or attributed to imperfections of the experimental samples. To that effect Kuhn cites interesting psychological experiments in which the participants failed to notice playing cards in which the suits are painted in the wrong color as long as the frequency of the tempered cards was low. This phenomenon is known in psychology as *confirmation bias*, a tendency to believe things that fit in one's wordlview.

Genuine anomalies will become known and accepted by the community, however, the simple appearance of anomalies does not falsify the paradigm. According to Kuhn "there is no such thing as research in the absence of any paradigm" (Kuhn 1962, p.79). Therefore, an anomaly cannot invalidate a paradigm if there is no competing paradigm to replace it. Kuhn argues that Popper's idea of falsification would amount to essentially stopping all scientific activity after the appearance of an anomaly. In practice this never happens. Instead, scientists try to patch up the model to accommodate the anomalies in the best way possible. The logic behind this behavior is that, despite a few unexplainable anomalies, the predictive power of the paradigm is still great, and it does not pay to abandon it, especially if there is nothing else to replace it with.

4. Crisis

The incidence and the importance of the anomalies become so great that the scientists lose faith in the paradigm. Kuhn calls this stage a *crisis* – "paradigm-testing occurs only after persistent failure to solve a noteworthy puzzle has given rise to crisis" (Kuhn 1962, p.145). At this stage, the discussion returns to fundamentals and there could be multiple conflicting schools advocating alternative models. In that respect, the state of crisis is similar to the pre-paradigm state.

Kuhn explores how the work under normal leads to crises in *The Essential Tension* in the context of the interplay of creative and convergent thinking (Kuhn 1977d). He argues that part of the scientific development are revolutions. Since revolutions do not simply add to the existing knowledge creative thinking is necessary. However, most of the scientific development is normal science, which requires highly convergent thinking. Kuhn coins the phrase *essential tension* to describe the conflict between the two modes of thought.

In natural sciences education is based on textbooks which give the current state of the paradigm without alternatives and without historical background. This encourages convergent thinking. Ideally students should learn what is known, but they also should learn about open problems, techniques to approach these problems. However, critics argue that this aspect has been completely ignored by the science education. Kuhn's response is that science education has not always been rigid, but it is precisely the moment it becomes dogmatic that is associated with great acceleration of scientific progress. Creativity is emphasized in sciences that do not have a dominant paradigm, i.e.

they are in a pre-paradigm or crisis state. Since there is no dominant paradigm, the student is exposed to several competing paradigms and spends his effort on evaluating one paradigm against the other. This encourages creativity and divergent thinking but not much progress is made. On the contrary normal science is solving problems within the paradigm. Rigid education gives the student the tools to be proficient and productive in solving these types of problems.

Furthermore, Kuhn thinks that precisely the adherence to tradition is what caused change in the tradition. Embarking on new problems for creativity's sake is does not pay off because the return of the effort is very low. The switch to creative mode is more subtle and efficient. Discoveries do not come from search for novelty, but from events when something goes wrong in the process of normal research. People embark on esoteric, difficult problems only because they believe that they have solutions under the current paradigm. Which is normal because the current paradigm is the only one that can promise a solution. But when the solution runs into trouble this forces the scientist to switch to creative mode. Thus, Kuhn points out at an essential dichotomy between convergent and divergent thinking. A scientist has better chance of being productive if sticking to tradition, but he has to have the flexibility to recognize when an opportunity for a creative development arises.

5. Revolutionary science

During the crisis the agreement among scientists is broken and they feel free to explore alternative models. Kuhn calls this *revolutionary science*. Kuhn defines a revolution as "non-cumulative development episodes in which an older paradigm is replaced in whole or in part by an incompatible new one" (Kuhn 1962, p.92). Anomalies cause revolutions because they cannot be explained in the old paradigm. Then a new paradigm is required to resolve them, but the new paradigm makes contradictory predictions to the old one. Thus, the new paradigm must displace the old one. In a work entitled *What are Scientific Revolutions?* Kuhn argues that revolutionary changes are holistic (Kuhn 2000d). Changes cannot be incorporated. They either cause incoherence in the theory or a number of related generalizations have to be revised together. Only the initial and final set of concepts provide coherent account of nature.

The research during a revolutionary period is not cumulative since most of the developed models are eventually abandoned. The successful model is not continuous with the previous paradigm in a couple of ways. First, there can also be some initial loss in understanding, because in the beginning the new paradigm has not had the time to revisit and reformulate many of the problems that have explanations under the previous paradigm. In addition, the new paradigm it represents a discontinuous jump in its predictive power. This sort of research is *intensive* in the sense that it opens new dimensions to explore, rather than exploring the existing dimensions.

6. Paradigm shift

One crucial implication of this wholesale replacement of the paradigm is the idea of *incommensurability*. The term simply means no common measure and expresses the idea that since the new paradigm has no shared points with the old one, there is nothing to serve as a measure or a standard of comparison. In other words, each paradigm develops its own sets of concepts that cannot be directly compared with each other. Kuhn observes that in formulating new paradigms scientists reuse the familiar terms from the existing paradigm, but the meaning of the terms is changed, and they stand in different relationships among themselves.

Due to incommensurability the process of transition from an old paradigm to a new one is not a straightforward one. Kuhn argues that there are objective reasons to prefer one paradigm over the other, such as that it solves more problems or that it gives better qualitative agreement with experiment, but these reasons are not sufficient. It is likely that at its inception the model explains little and could be at par or even inferior to existing models. Instead Kuhn describes what is essentially a consensus-based mechanism. He says that "any new interpretation of nature, whether a discovery or a theory, emerges first in the mind of one or a few individuals" (Kuhn 1962, p.144). Other scientists are then drawn to the paradigm for what Kuhn calls "subjective and aesthetic considerations" (*ibid*. 156). The attractiveness of the model is based on "less on past achievement than on future promise" to be compatible with all preexisting knowledge and, in principle, to explain it, in addition to promising to generate new predictions and discover new knowledge. Since there is not sufficient objective basis to choose the new paradigm "decision of this king can only be made on faith" (*ibid*. 158).

This community further develops the paradigm to the point where it advantages become more pronounced. Therefore, more and more scientists adopt the paradigm and gradually the support for the old paradigm dies out, although this frequently requires a generation change because adherents of the old paradigm are too invested in the paradigm to abandon it. The winning paradigm again rally the scientists and usher another period of normal science.

To summarize, Kuhn's picture of the scientific development over time is one of alternating periods of normal science, crisis, and revolutionary science. During the normal science the scientific community is unified by a dominant paradigm. The lack of disagreement on fundamentals gives the paradigm the appearance of absolute truth. The research is focused on elaborating the paradigm and it is cumulative. The crisis is caused by the accumulation of anomalies, that appear as part of the ordinary work done under the normal science, causing the community to lose faith in the paradigm. It is followed by a period of revolutionary science during which alternative paradigms are proposed and explored. The work during this period is not cumulative, as most of it is discarded; the successful paradigm causes a discontinuous jump in understanding.

The obvious target of the mechanism proposed by Kuhn is the preconception that scientific development is continuous and cumulative. Philosophers of science before Kuhn saw scientific development as continuous in the sense that each scientific theory builds upon the previous and incorporates it. In the Kuhn's picture the new theory is incompatible with the old and displaces it. During the transition there is a loss of knowledge, therefore it is discontinuous.

Beyond the obvious message, however, there are deeper undercurrents. Kuhn is an internal realist. His picture is essentially one of perceiving the world through a representation where the paradigm determines the categories through which the world is interpreted. However, in Kuhn's view consecutive paradigms are incommensurate amongst themselves. Furthermore, there is no evidence that a paradigm develops towards an asymptotic description of the world-in-itself, as the classical philosophers of sciences believed. As a consequence, Kuhn denies that there is a criterion of truth outside the paradigm. This leaves the choice between the paradigms to be governed by a different rational process, which he describes as consensus-based where each member of the community chooses the paradigm for reasons beyond pure logical justification as believed by the classical philosophers of science.

In fact, in the last chapter of the *Structure* entitled *Progress through Revolutions*, Kuhn went as far as to compare scientific development to biological evolution. Scientific development, he says, moves "from primitive beginnings but toward no goal" (Kuhn 1962, p.172). The successive stages of the process are "marked by an increase in articulation and specialization" (*ibid*. p.172). And the process occurs "without benefit of a set goal, a permanent fixed scientific truth" (*ibid*. p.173).

III. After the Structure

With the publication of the *Structure* Kuhn ushered the new philosophy of science. In the *Structure* the prevailing discourse in the philosophy of science was essentially disregarded and the focus was shifted from logical justification to historical induction. Its disruptive role can be best stated in the language of the *Structure* itself: the philosophy of science before Kuhn was in a state of crisis during which the existing paradigms were faced with a myriad of anomalies (unanswerable questions or contradictions) and the practitioners had lost faith in the paradigms. Kuhn's theory was the product of a revolutionary science period. It introduced a new paradigm that is mostly incommensurate with the previous paradigms.

Not surprisingly Kuhn's thesis in the *Structure* attracted a great deal of criticism from the representatives of the traditional school of philosophy of science. As a result, Kuhn spent the remainder of his career trying to explain, justify, and elaborate his thesis. The lines of criticism span all the ideological dividing lines between the incumbent philosophy of science and Kuhn's radical views.

1. Methodology

Kuhn heralded the historical method in the philosophy of science. His insights in the *Structure* result from generalizations of historical exemplars of scientific revolutions. In fact, Kuhn's first work on the Copernican revolution (Kuhn 1957) was a work on history of science, but the tendency of far fetching generalization is evident there as well. The focus of the *Structure* is shifted toward the underlying commonalities among the historical examples of scientific revolutions, although the text still consists mostly of description and discussion of the examples that led to and support these generalizations.

In contrast, the incumbent view of the philosophy of science was that the rules governing science could not be historical incidents, they must be immutable and universal. Furthermore, logic provides the only solid foundation for determining these rules. Respectively, Popper criticizes Kuhn's method on the basis that history and sociology are not reliable sciences and no conclusions pertaining to science can be made from such foundations (Popper 1970). Watkins makes a similar argument from a slightly different perspective. He claims that philosophy of science is concerned with ideal science, "as it should be conducted", rather than with the imperfect way it is actually practiced which is what Kuhn is describing (Watkins 1970, p.27).

Kuhn dismissed the notion that there is much difference between his methodology and that of his critics. In the *Reflections on my Critics* he says that all practitioners of the philosophy of science "do historical research and rely both on it and on the observation of contemporary scientists" in developing their theories and that they can be "scarcely distinguished by our methods" (Kuhn 1970, p.233). Furthermore, he accuses his critics of "employing a sleight of hand to reserve the philosophical mantle" for themselves (*ibid*, p.233). In the *The Relations between the History and the Philosophy of Science* Kuhn addresses the issue in greater detail (Kuhn 1977e). He acknowledges that "history and the philosophy of science are separate and distinct disciplines" (*ibid*. p.4) with history being "an explanatory enterprise; yet its explanatory functions are achieved with almost no recourse to explicit generalizations" while philosophy "aims principally at explicit generalization and those of universal scope" (*ibid.* p.5). Nevertheless, Kuhn makes the case that the study of history can greatly benefit the philosophy of science because it provides it with examples based on which to make sweeping generalizations.

It is worth mentioning that although Kuhn does not provide a convincing answer to the critique of the inductive derivation of his theory, he stumbles on an inconvenient truth that that this is exactly what the traditional philosophers of science do as well, making generalizations based on observations of how science is practiced.

2. Paradigm

Kuhn uses the word paradigm in the sense of model or template, but as he himself admits in the *Structure*, the word is used to "often substitute for a variety of familiar notions" (Kuhn 1962, p.11). Indeed by accounting for the context in which the word paradigm is used, more than twenty nuances of the word use in the *Structure* have been identified (Masterman 1970). The lack of a clear definition of the term prompted the critics to label the concept as vague and therefore void of meaning (Shapere 1964).

This line of critique prompted Kuhn to try to disambiguate the meanings. He returned to this issue a number of times. In most detail Kuhn addresses the problem first in the *Postcript-1969*, published seven years after the *Structure* (Kuhn 1962). Later, in *Second Thoughts on Paradigms* (Kuhn 1977c), he gives a similar account of his updated view of the paradigm concept. In these works, Kuhn defines paradigm as the entire constellation of beliefs shared by a scientific community as well as a set of particular defining examples (exemplars) that serve as models or templates for doing normal science.

Kuhn states that community structure is essential to the definition and understanding of paradigms. In the *Reflections* he states that "a new version of my Scientific Revolutions would open with a discussion of community structure" (Kuhn 1970, p.271). He points out that a scientific community can be identified without recourse to paradigms. Instead criteria for belonging to a community can be schools attended, membership in professional societies, journals read, etc. Communities are both the producers and validators of scientific knowledge. In the context of scientific communities, a paradigm can be defined as the set of ideas that a scientific community shares.

Kuhn also greatly expands on the definition of a paradigm. He proposes that a more appropriate name for paradigm would be a *disciplinary matrix*. Disciplinary because it is shared among the practitioners of a discipline and a matrix because it contains several components. The first component of a disciplinary matrix are *symbolic generalizations*.

These are deployed without justifications and often stated in logical or mathematical form. Some generalizations are definitions (axioms) and some generalizations (empirical relations, laws). The difference is that laws are corrigible but the definitions are not.

On the second component Kuhn's account differs between the *Postscript-1969* and the *Second Thoughts on Paradigms*. In the *Postscript* Kuhn calls this component of the disciplinary matrix *metaphysical beliefs*. In the *Second Thoughts* he calls it *models* which are "objects of metaphysical commitment" (Kuhn 1977c, p.298). In either case they provide the community with ontology. These principles are not laws and are not derived from experience but have far reaching consequences in organizing experience. Examples include conservation of energy, conservation of mass, or conservation of electric charge.

The third component of a paradigm are *values*. This are principles shared by the community of how science should be practiced. These include for example preference for quantitative over qualitative explanations, desire for accuracy and acceptable margins of error, necessity for consistency, simplicity, etc. The values are extremely important during a crisis for transition between paradigms when there are no other criteria for choosing one paradigm over the other. Although values are shared by the community individual members of the community may vary in their application. This possibility of personal or subjective preferences in the selection of a paradigm if the cornerstone of accusation of subjectivity and irrationality. Kuhn gives a more detailed account the criteria used in the choice of theory in *Objectivity, Value Judgement, and Theory Choice* (Kuhn 1977b) where he identifies five major values shared by the scientific communities. Accuracy is the desire to demonstrable, both quantitative and qualitative agreement with experimental observations. Consistency to make internally consistent and also consistent with he currently accepted theories. Scope such as the consequences should extend beyond the scope of the particular observations. Simplicity to bring order to a set of disjointed and confused phenomena. And fruitfulness to open grounds for discovery of new phenomena and relationships between phenomena.

The forth component of a paradigm are *exemplars*. These are concrete problem solutions that can be used as models or templates to solve similar problems. Kuhn argues that the examples are as important as the theory for understanding nature. Problems are solved not by starting from fundamentals but by mapping them on other solved problems. This is the typical operation of normal science. Puzzles are solved by modeling them on the solution of other puzzles, not based on fundamental laws.

Overall, despite Kuhn's elaboration of the paradigm concept, it remains loosely defined and it signifies different things in different contexts. The reason is that Kuhn derives his generalizations about paradigms from historical examples and in his writing he leans heavily on the intuitive preconceptions of concept of scientists and philosophers. Clearly a better and stricter definition of the term is needed.

3. Normal science

The concept of normal science in Kuhn is also problematic. He defines it as the activity of solving problems within the paradigm without challenging the foundations of the paradigm itself. However, critics have challenged the existence of normal science in the sense of Kuhn. Popper argues that all science is revolutionary, because it is the nature of science to test hypotheses and try to falsify the predictions of the paradigm (Popper 1970). Thus, Kuhn's concept of normal science as "puzzle-solving" does not fall in the domain of science. Popper says that Kuhn's normal scientist is just "badly thought" and a "victim of indoctrination" (ibid. p.53). According to Popper this type "may be called an applied scientist, in contradistinction to what I should call a pure scientist" and he is "a person one ought to be sorry for" (*ibid*. p.52,53). Popper also mentions that between the "'normal scientist' and his 'extraordinary scientist' there are, I assert, many gradations; and there must be" (ibid. 54). In a similar vein, Toulmin challenges Kuhn to give a criterion for a distinction between normal and revolutionary science (Toulmin 1970). He writes that the binary distinction between normal and revolutionary science is untenable and what we observer in fact are "greater and lesser conceptual modifications differing from one another in degree" (ibid. p.45).

Kuhn's addressed this critique in *Reflections on my Critics* (Kuhn 1970). Unfortunately, the response is unconvincing. The logic of Kuhn is "if there are revolutions, then there must be normal science" (*ibid*. p.249). In other words, we can clearly recognize revolutions in the historical record, but there is a different type of science in the intervening time. Additionally, Kuhn also gives a number of historical examples of revolutions and contrasts them to the standard scientific practice, such as the transition of geocentric to heliocentric astronomy is a revolution, but the discovery of Neptune is not. The tacit logic of this argument being that the practitioner can tell normal science from revolutionary science when he sees it. The problem with both these arguments is that, although science is practiced differently in the periods between revolutions, it does not follow that this practice fit the description of normal science that Kuhn gives.

Interestingly, the critique of the mundane notion of normal science leads to an exciting proposition. Toulmin compared Kuhn's dichotomy of revolutions and normal science to "catastrophism" which captures the idea that normal development is occasionally interrupted by major conceptual shifts (Toulmin 1970, p.44). Instead, "conceptual incongruities", Toulmin suggested, "are liable to turn up much more frequently". He concludes that "we are left with only a sequence of greater or lesser conceptual modifications differing from one another in degree" (*ibid.* p.45). In other words, revolutions come at different scales. To this point we will return in the next chapter.

4. Incommensurability

In the Structure, Kuhn introduced *incommensurability* as the lack of common measure between paradigms which arises from the incompatibility of worldviews. It expresses the idea that since the new paradigm has no shared points with the old one, there is nothing to serve as a measure or a standard of comparison. In other words, each paradigm develops its own sets of concepts that cannot be directly compared with each other. Kuhn observes that although in formulating new paradigms scientists reuse the familiar terms from the existing paradigm, the meaning of the terms changes and they stand in different relationships among themselves.

In the *Road since Structure* Kuhn explains that the notion of incommensurability emerged "from attempts to understand apparently nonsensical passages encountered in old scientific texts" (Kuhn 2000b, p.91). In this Kuhn is on the same boat with all practicing scientists. Not only it is nearly impossible to comprehend the logic of works from older schools of thought, but it is even extremely difficult to read the original works that established the current paradigm, because they are to a large extent still written in the language of the preceding paradigm.

Of course, it is preposterous to believe that scholars of the caliber of Aristotle and Ptolemy and generations of their followers could have been wrong to such an extent. Therefore, Kuhn arrived at the notion that they were reasoning from the point of view of different worldviews. Reading and interpreting their works through the prism of our modern worldview is a mistake, because although the words are the same, they express different ideas and stand in different relationships among themselves in the two worldviews (Kuhn 1962). Thus, statements of the old worldview do not make sense in the new worldview.

Therefore, the only way to understand the old scientific texts is to assimilate the set of ideas available to their authors and read their works with their set of concepts in mind, abstracting oneself from the modern notions. This amounts to what Foucault calls "archaeology of knowledge" (Foucault 1969). In the language of Foucault, systems of thought or *epistemes* are governed by rules that define the conceptual possibilities in the language of a given domain and period. Thus, Foucault's notion of episteme is largely equivalent and better elaborated version of paradigm.

Kuhn's notion of incommensurability in the *Structure*, as the choice of the word itself suggests, was extreme. This extreme notion reflects the scale of exemplars of which Kuhn is thinking, such as the transitions from the Ptolemaic astronomy to the Copernican and from the Aristotelian physics to the Newtonian. In these cases Kuhn is justified to claim that scientists who espouse different paradigms live in "different worlds" and that they are "themselves different" (Kuhn 1962, p.120,121).

The problem is that not all revolutions are of this scale and the critics, such as Lakatos and Toulmin, were quick to point out examples where the worldviews before and after the revolution share a lot of concepts and there is a fairly easy translation from the one set of concepts to the other (Lakatos 1970; Toulmin 1970). As mentioned earlier, Toulmin labeled Kuhn's view as "catastrophism" an argued that revolutions have different scales (Toulmin 1970, p.44). Similarly, Popper argued against untranslatability between scientific theories. He said that it is "a dangerous dogma" that "the different frameworks are like untranslatable languages" pointing out that people routinely translate between the existing languages (Popper 1970, p.56).

In response to the criticism, in *Reflections on My Critics* Kuhn introduces a new way to explain incommensurability by analogy with translation between natural languages (Kuhn 1970). He elaborates this concept in *Commensurability, Comparability, Communicability* (Kuhn 2000a) and returns to the language analogy in the *Road since Structure* (Kuhn 2000b) although he states the "language metaphor" is meant to be an illustration, not an explanation (*ibid*. p.92).

Kuhn states that the words (concepts) in a language stand in established relationships with each other which he calls "lexical taxonomy" (Kuhn 2000b, p.92). Language imposes structure on the world. Each individual term is a node in the lexical network. They are connected together in a multidimensional structure which mirrors the relations between objects in the world and simultaneously limits what the language can describe. Here Kuhn makes the concession to reduce the scope of incommensurability. While in the *Structure* scientists working in "different worlds" implies global scope, here he admits that the paradigms (or lexical taxonomies) may overlap to a large extent and differ only in part. Incommensurability is then untranslatability "*localized* to one or another area in which the two lexical taxonomies differ" (*ibid*. p.93). Thus, although there are still statements that can be made in one taxonomy but cannot be made in another, this incompatibility is now local and not necessarily worldview-changing. This limited version Kuhn calls *local incommensurability* (Kuhn 2000a).

However, this does not mean that the taxonomies are not comparable. Kuhn makes the argument by deepening the analogy to make a distinction between translation and interpretation. He defines translation in the sense of Quine (Quine 1960). The translator knows both languages and possesses an equivalence table of phrases. He translates by replacement of terms from one language to another based on the equivalence table. Clearly incommensurability implies that the correspondence tables are incomplete and complete translation is not always possible. Interpretation, on the other hand, is when the scientist knows only one language and tries to divine the meaning of the other language. A process essentially equivalent to learning the language. Understanding a different paradigm is interpretation, i.e. learning the language (taxonomy) of the paradigm. Some lexical taxonomy is a prerequisite for communication. If members of a language community share a network and no translation is needed. Then if members of different communities that speak mutually translatable languages can go by translation. Their lexical taxonomies are isomorphic. Finally, when taxonomies are not isomorphic language acquisition is required.

5. Relativism

The term relativism has been used in many contexts and there are multiple definitions of it. However, it generally means that true and false judgements are "products of differing conventions and frameworks of assessment and that their authority is confined to the context giving rise to them" (Baghramian and Carter 2018). In other words, there is no absolute measure which allows to compare two independent and internally consistent frameworks. The term has negative connotations because it implies that if truth is purely subjective then no meaningful knowledge is possible.

This definition of relativism fits well Kuhn's position in the *Structure*. Kuhn argues that within the paradigm the truth value of a statement can be easily evaluated, i.e. a statement is true if it is consistent with the paradigm. However, when working with two incommensurate paradigms a statement can have a true/false value in one paradigm but not in another and has no meaning outside of a paradigm. Since Kuhn denies that there could be perception independent of any paradigm, then there is no measure external to both paradigms which can be used to compare them (Kuhn 1962). If there is no objective way to compare the two paradigms, then it is not possible to prove that one is wrong and there is a sense in which both can be right. This view is at odds with the classical philosophers of science, like Popper, who believe that scientific theories approach asymptotically the world-in-itself and therefore they can be compared on the basis of how much closer they are to it (Popper 1962).

In the *Reflections*, Kuhn rejects the connotation that his view implies that no knowledge is possible (Kuhn 1970). However, he argues that the traditional philosophers of science make a mistake in not recognizing the difference between "inter- and intra-theoretic" use of the word truth (*ibid*. p.264). He also rejects the notion of the classical philosophes of science that theories can be compared on the basis of how close they are to the "what is really out there". He writes that "it is far from clear how the phrase 'more like' is to be applied" (*ibid*. p.265). The presumption that we can compare paradigm to the world-in-itself is simply wrong and the idea of the world-in-itself is simply an extrapolation of the development of the paradigm. However, Kuhn claims that the "comparison of historical theories gives no sense that their ontologies are approaching a limit" (*ibid*. p.265).

6. Irrationality

In the view of the critics, the problems of incommensurability and relativism lead to irrational choice between competing paradigms during transitions. Kuhn argued in the *Structure* that objective criteria, such as solving more problems or better quantitative agreement with experiment, are usually not sufficient for make the choice of one theory over the other. He also shows in *Objectivity, Value Judgment, and Theory Choice* that such criteria evolve over time, are not applied the same by different individuals, and the application of the criteria frequently leads to contradictions (Kuhn 1977b). Therefore, in addition to these criteria, each scientist uses other "subjective and aesthetic considerations" to commit to a paradigm and the paradigm is accepted to a large extent in “faith” (Kuhn 1962, p.156,158). He also shows that the community dynamics is important for the choice of a paradigm and factors such as persuasion and authority are of consequence.

Kuhn’s reference to psychological and sociological factors in the choice of paradigms was encountered with fierce critique. In *Normal Science and its Dangers*, published in the collection *Criticism and the Growth of Knowledge*, Popper rejects the notion that there is no rational criterion for the choice of a paradigm (Popper 1970). According to Popper’s own theory, successive theories encompass the previous theories and therefore the choice of the more comprehensive theory is rational (Popper 1934). In *Normal Science and its Dangers* Popper insists that there is “’absolute’ and ‘objective’ truth” beyond the limits of a paradigm (Popper 1970, p.56) and correspondingly that the criteria for choosing between competing paradigms are “not psychological or historical – they are logical”. He believes that the Kuhn’s statement that scientific (and therefore rational) work is only possible inside a paradigm is “a logical and philosophical mistake” (*ibid*. p.56). Popper’s view is that at any given moment we use a framework, but we can escape from it at wish and we can always compare frameworks. He also dislikes Kuhn’s metaphor of incommensurate paradigms as untranslatable languages and says that this is just a “dangerous dogma” (*ibid*. p.56) that arises from overstating the difficulties of the translation. As a counterexample Popper gives translations between widely different natural languages such as Chinese and English. He reiterates multiple times his thesis that scientific knowledge “may be regarded as subjectless” and concludes that the “logic of discovery has little to learn from the psychology of research” (*ibid*. p.57,58).

Lakatos uses similar strong words to describe Kuhn’s ideas in his principal work *Falsification and the Methodology of Scientific Research Programmes* (Lakatos 1970). He believes that Kuhn’s views are essentially a rejection of the naïve falsificationism proposed by Popper, but claims that Kuhn “excludes *any* possibility of rational reconstruction of the growth of science” and that in Kuhn’s view “there can be no logic, but only psychology of discovery” (*ibid*. p.177,178). It is clear that Lakatos believes that his own brand of “sophisticated falsificationism” rescues the rational choice between paradigms. Lakatos then continues with the analysis of Kuhn’s theory of scientific revolutions and claim that “there is no rational cause for the appearance of Kuhnian ‘crisis’” and that crisis is a psychological concept equivalent to “contagious panic”. Lakatos dismisses Kuhn’s community consensus theory of paradigm choice as a “bandwagon effect” and concludes that Kuhn’s view of scientific progress is “irrational, a matter of mob psychology” (*ibid*. p.178).

Similar critiques abound. For example, Scheffler in his *Science and Subjectivity* summarized Kuhn’s theory of scientific progress as “adoption of a new scientific theory is an intuitive or mystical affair, a matter for psychological description rather than logical or methodological codification” (Scheffler 1967). Shapere in *Meaning of Scientific Change* also reacted strongly to Kuhn’s suggestion that there could be a psychological element, such as influence or persuasion, in the choice of one theory over the other (Shapere 1966).

Kuhn did not take the accusations of irrationality lightly. In the *Reflections*, Kuhn writes that he was “dumbfounded” by the suggestion that he advocates the notion that scientists do not use logic and that scientific progress is irrational (Kuhn 1970, p.261). He also says that “to describe the argument as a defense of the irrationality in science seems to me not only absurd but vaguely obscene”. Instead Kuhn declares that the existing notions of rationality are obsolete and “we must readjust them or change them to explain why science works as it does” (*ibid*. p.264). In the *Logic of Discovery or Psychology of Research* he makes a profound critique of Popper and the traditional notion of rationality (Kuhn 1977a).

Kuhn rejects Popper’s idea of hypothesis testing (Popper 1934). He says that fundamentals testing rarely happens in the way how science is practiced. Instead testing happens in the process of normal science. The scientist tries to solve a puzzle the solution of which is presupposed by the paradigm. He makes hypotheses and tests them. If his hypotheses are rejected and he does not manage to solve the problem, this is a personal failure. The premises of the paradigm are never tested, they are in fact the rules applied to solve the puzzle. Thus, Kuhn claims that, first, Popper’s theory leaves out most of scientific activity outside of science and considers only the revolutionary episodes as science. Second, Popper's description of how science is practices is essentially by Socratic argument and criticism. Kuhn argues that that only happens in the pre-paradigm state and during crises. In fact, science starts when discussion ends. Instead, Kuhn proposes that under certain circumstances personal failures to solve puzzles can become a catalyst for the opinion of the community to change. The failure is accepted as an anomaly and failure of the theory. Since it arose from within the paradigm, it is harder to ignore. Thus, normal science prepares the way for its own displacement, it leads naturally to revolutionary science.

Furthermore, Popper claims that science advances through conjectures and refutations which is essentially the practice of learning from our mistakes (Popper 1962). Mistakes again appear within the practice of normal science when an individual does not apply the rules of the paradigm correctly. Usually the community can catch these problems, and this is how they are categorized as mistakes. However, what Popper means by mistake is that the theory was wrong, and it is identified when the theory is replaced by another. This is a different kind of mistake, an error of induction, that the incorrect theory is induced from experience. No mistake is made in proposing new theories (e.g. Ptolemaic).

Overall, Kuhn argues both the concepts of test and mistake have been lifted from the practice of normal science where they have well-defined meaning and applied to revolutions where they do not. The transfer of the concepts of testing and mistake creates the illusion that there are criteria which govern the succession of theories. Instead Kuhn says that it cannot be shown that theories discover the truth about nature nor that they approach asymptotically the truth. If there is progress, then it is towards no goal. In the *Reflections* Kuhn laid the foundation for this new notion of rationality by saying that his "view of scientific development is fundamentally evolutionary" (Kuhn 1970, p.264). The development of science is "unidirectional and irreversible" but not towards any goal (*ibid*. p.264). This echoes the last section of the *Structure*, where Kuhn argued that the greatest achievement of Darwin's theory of evolution is the rejection of teleology. Evolution is a process that produces "gradual but steady emergence of more elaborate, further articulated, and vastly more specialized organisms" with "no goal set either by God or nature" (Kuhn 1962, p.172). Similarly, scientific progress is driven by selection because "one scientific theory is not as good as another for doing what scientists normally do" (Kuhn 1970, p.264). This process does produce improvement of scientific theories, for which reason Kuhn sternly denies the notion that he is a relativist. In Kuhn's analysis the label reflects his rejection of the teleology of Popperian philosophers of science, which is nothing more than an atavism inherited from religion.

IV. Beyond the Structure

From the vantage point of a scientist, the very first thought which comes to mind after reading Kuhn's work is that it is mostly common sense and that the conclusions are rather obvious. There could be two alternative explanations for this. One explanation is that the paradigm proposed by Kuhn has become dominant and the thinking of modern-day scientists is molded by it. Another explanation could be that scientists have always thought that, and Kuhn just recorded the common wisdom. Although we cannot know the state of mind of pre-Kuhntean scientists, the stories about the discoveries of Copernicus, Newton, Einstein, etc. are such an integral part of scientific folklore that it would be surprising if anyone before Kuhn would have been shocked if these discoveries were interpreted as revolutions which steered ordinary science in whole new directions. On the other hand, it is not at all surprising that to a non-scientist who, for example, would not know and would not understand the difference in the postulates of classical mechanics and special relativity, the statements that scientific progress is not continuous and that there is no special justification of scientific theories other than that they work would appear unnerving.

That was certainly the reaction of the traditional philosophers of science at the time, who levied severe criticism on some of the principal postulates of Kuhn's theory, such as paradigm, normal science, and incommensurability, as well as the perceived consequences of Kuhn's theory, such as relativism and irrationality. Although, Kuhn spent a good deal of his career after the publication of the *Structure* defending and clarifying his ideas, his efforts are not very convincing and generally failed to resolve the issues. To a large extent the problem is methodological, as some of the critics pointed out (Popper 1970; Watkins 1970). Kuhn's theory is based on sweeping generalizations from historical exemplars. The nature of this approach is inductive. Induction is a great tool for the purpose of formulating new hypotheses, but as Hume pointed out (Hume 1748), the hypotheses cannot be defended by merely giving more examples, which was what Kuhn attempted on many occasions. Similarly, a hypothesis cannot be proven by constructing analogies or metaphors to illustrate the point, which is essentially what Kuhn did in comparing incommensurability between scientific theories with translatability between natural languages.

On the other hand, generalizations from historical exemplars can be used to formulate a model of scientific development based on a few fundamental assumptions that captures all of Kuhn's observations and can be also used to appraise criticisms and possibly reach conclusions that extend the current discourse. This model should consist of two components: a static component, which is the representation of the state of scientific domain at a particular point in time, and a dynamic component, which is the mechanism governing the change of these representations.

Before we stipulate the model, we need to introduce some key concepts.

1. More is different

To begin, it is useful to establish some parallels. The first parallel is between scientific and economic development i.e. compare Kuhn's theory of the structure of scientific revolutions with the dialectic materialism of Marx and Engels (Marx 1867). Kuhn himself borrowed the term revolution to describe scientific change by exploring the parallel with political development which he develops in the chapter on the nature and necessity of scientific revolutions in the *Structure* (Kuhn 1962). Marx and Engels introduced the historical approach in the study of economic order. In the language of the *Structure*, history can be divided in periods of *normal economy* characterized by steady economic relations within the society. During the normal periods the society is productive and the results cumulative. Class tensions eventually lead to crisis during which the faith of the population in the existing economic order is lost. The crisis is followed by a revolution which establishes a new economic order. The economic output during the revolution is non-cumulative as many of the structures inherited from the old economic order are destroyed or restructured. The new economic order has superior economic relations in terms of increased productivity.

Another interesting parallel is with the punctuated equilibria theory of biological evolution of Gould and Eldredge (Eldredge and Gould 1972; Gould and Eldredge 1993). According to this hypothesis, evolution can be viewed as long periods of *stasis* punctuated by bursts of rapid change and expansion. In the *stasis* period there is very little change in the phenotype of the species. Presumably the species are well adapted to their environments and effectively resist change. Instead of changing, they expand in the habitat and compete with other species for resources. As they do so they change the environment (the environment can also change due to external reasons, such as climate change). This brings forth crises, presumably when the habitat can no longer support the populations. The crises set forth periods of a rapid genetic change, with new species forming at an accelerated rate, as the species adapt to the new conditions. The new species are better adapted to survive under the new conditions. Kuhn himself makes this parallel between scientific revolutions and evolution by natural selection of organism on a number of occasions, most notably in the *Road since Structure* (Kuhn 2000c).

The similarity between the structure of economic order, biological evolution, and scientific revolutions is due to the fact that they all exhibit the typical behavior of *complex systems*. In recent decades, developments in mathematics, biology, physics, economics, and informatics are converging from different angles on the problem of what has become known as complex systems (Holland 1995). The characteristic feature of these systems is that interactions between simple parts of a system give rise to the complex collective behavior of the system or spontaneous order. The existence this order of the system cannot be inferred from the properties of the parts.

In philosophy the idea of spontaneous order was introduced by Hegel, but it a more tractable formulation was given by Marx in *The Capital* – "merely quantitative differences, beyond a certain point, pass into qualitative changes" (Marx 1867). In physics spontaneous changes in order are known as phase transitions (Landau 1936). The philosophical implications of the idea were discussed by the Nobel Prize winning physicist Philip Anderson in a famous paper entitled *More is Different* (Anderson 1972). The fundamental operating principle of science in general and physics in particular is the *reductionist hypothesis* i.e. the vast phenomenology of nature can be reconstructed from the interaction of a few fundamental objects (van Riel and Van Gulick 2018). Anderson argued against this proposition and stated, because "at each level of complexity entirely new properties appear" (Anderson 1972). The appearance of spontaneously order is exemplified by the *emergence* of new properties (Holland 1999). Most importantly this complexity is self-organized, not designed (Prigogine 1984; Kauffman 1993).

In a sense, reductionist science works remarkably well in the quantitative phase i.e. between transitions. The phenomenology of a particular phase of matter can be described by means of a set of a few fundamental objects and the interactions between them (natural laws). However, the phase transitions act as an irreducible barrier. Beyond this barrier new fundamental objects appear that interact according to a different set of laws.

(a) The structure is the properties

A complex systems can be represented as a collection of fundamental objects or *agents* that act according to a set of simple rules. Typically, the interactions are pairwise i.e. an agent only interacts with one other agent at a time. In this case the interactions between the agents can be represented by a network. Network science is an emerging field of science which purpose is to study the properties of complex systems arising from pairwise interactions between agents. The science of networks started with the pioneering work of Erdös and Rényi who developed the theory of random graphs (Erdös and Rényi 1959). Excellent reviews of the current understanding of networks can be found in Barabasi's *Network Science* (Barabási 2016) and Newman's *Networks* (Newman 2018). The mathematical representation of networks are objects called graphs, which consist of vertices and edges representing the objects and the connections between them respectively. The properties of the system can be inferred from the topological properties of the graphs.

- *Graph definition*

Formally, a network is represented by the mathematical concept of a graph. The graph is a pair of sets $G = (V, E)$ where V are vertices (nodes) and E are edges (arcs) between pairs of vertices. When E is a set of unordered pair of vertices the graph is said to be undirected or simple. In a directed graph E consists of an ordered set of vertex pairs. A graph is weighted if there is a map (weighting function), $w(E)$, assigning to each edge a positive weight (Barabási 2016). For example, in a undirected graph of four vertices (a-d)

and five edges (1-5) is shown in Fig. 1a, a similar directed graph with weighted edges is shown in Fig. 1b, and a larger graph with clustering is illustrated in Fig. 1c.

The properties of the network are determined by the structure of the graph. One of the most fundamental metrics is the distance on a graph. Vertices connected by an edge are said to be adjacent. A walk of length m in a graph G from a vertex u to v is a finite alternating sequence of vertices and edges $\langle \mathrm{v_0, e_1, v_1, e_2, \ldots, e_m, v_m} \rangle$, such that $o(e_i) = v_{i-1}$ and $t(e_i) = v_i$ for $0 < i \leq m$ such that $u = v_0$ and $v = v_m$. Then the number of edges traversed in the shortest walk joining u to v is called the distance in G between u and v denoted by $d(u, v)$. A walk whose vertices are distinct is called a path. A graph is said to be connected, if any two vertices are the extremities of at least one walk. For example, the graphs in Fig. 1a is connected. There are several possible paths between vertices a and d, such as a-1-b-3-c-5-d of length 3, a-2-c-5-d and a-3-c-5-d both of length 2, therefore, the distance between a and d is 2. In the directed graph in Fig. 1b there are only two such path because the path through edge 3 is no longer possible.

- *Topological properties*

The degree of a vertex is the number of edges that connect the vertex with other vertices. In other words, the degree is the number of immediate neighbors of a vertex or the number of edges coming out of the vertex. In a directed graph we can distinguish in- and out-degree which is the number of edges coming in and out of a vertex respectively. For example, for the graph in Fig. 1a the vertices have the following degrees $a(3)$, $b(2)$, $c(3)$ and $d(1)$. For the directed graph in Fig. 1b the in- and out-degrees are $a(1,2)$, $b(1,1)$, $c(2,1)$ and $d(1,0)$.

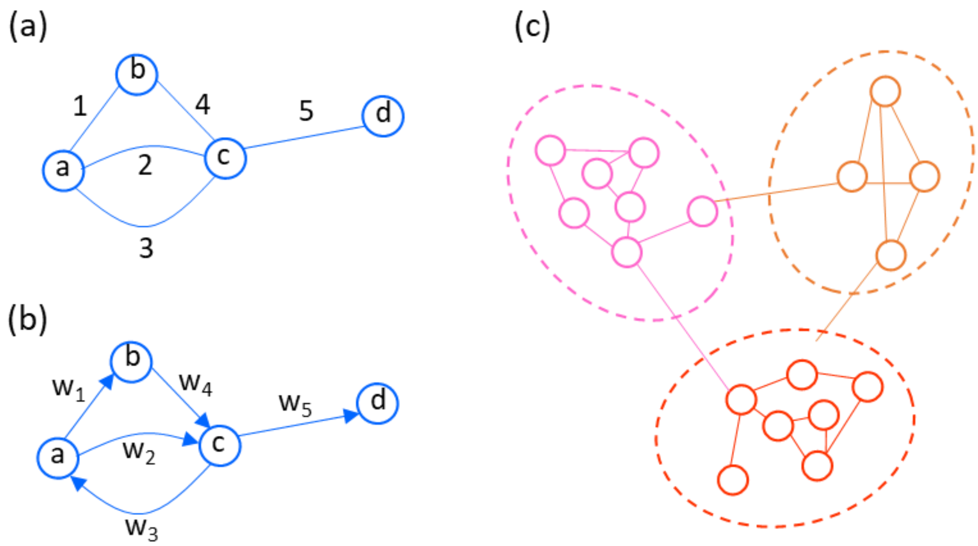

Fig. 1: Graph illustration: (a) undirected graph, (b) directed graph with edge weights, and (c) community structure of a graph (clustering). Node in the same cluster have mode connections with other nodes in the cluster than with nodes outside.

The degree distribution is the fraction of vertices of degree k, $P(k) = n_k/N$. Thus, the degree distributions can tell a great deal about the structure of a family of networks. For example, in random graphs the degree distribution is singly peaked, following the Poisson (or its Gaussian approximation) distributions, the majority of the nodes can be described by the average degree $\langle k \rangle$ (Erdös and Rényi 1959). In this case, there are typical nodes of the networks whose degree distribution is within a few standard deviations from the average, while the probability to find nodes with degree much different from the average decreases exponentially. Networks like that have no 'structure'.

In contrast, functional networks, like the ones that occur in biology and economics, have been shown to follow power-law degree distributions (Levinson 2004). The majority of the nodes have only few neighbors, while a few nodes have relatively large number of neighbors. The highly-connected nodes are known as hubs. The local clustering coefficient captures the degree to which the neighbors of a given node link to each other. Evidence suggests that in most real-world networks nodes tend to create tightly knit groups characterized by a relatively high density of connections that tends to be greater than the average probability of a tie randomly established between two nodes. The clustering coefficients can be used to characterize a network's *modularity*. Modularity is one measure of the structure of networks or graphs. It was designed to measure the strength of division of a network into modules (also called groups, clusters, or communities). Networks with high modularity have dense connections between the nodes within clusters but sparse connections between nodes in different clusters (Fig. 1c).

- *Scale-free networks and preferential attachment*

Many natural and artificial networks exhibit a degree distribution, described as scale-free. In a scale-free network the number of nodes n_k of degree k is proportional to a power of the degree, $n_k = k^{-\beta}$, where $\beta > 1$ is a coefficient characteristic of the network (Barabási 2016). Unlike in random networks, where the degree of all nodes is centered around a single value with the probability of finding nodes with much larger (or smaller) degree decaying exponentially, in scale-free networks there are nodes of large degree with relatively higher probability. The difference between random and scale-free degree distributions is illustrated in Fig. 2. Since the power low distribution decreases much more slowly than exponential, for large k, producing heavy or fat tails, scale-free networks support nodes with extremely high number of connections called *hubs*. The network properties in a scale-free network are determined by the local structures. As a consequence of a relatively small number of highly connected nodes or hubs the scale-free network are highly tolerant of random failures.

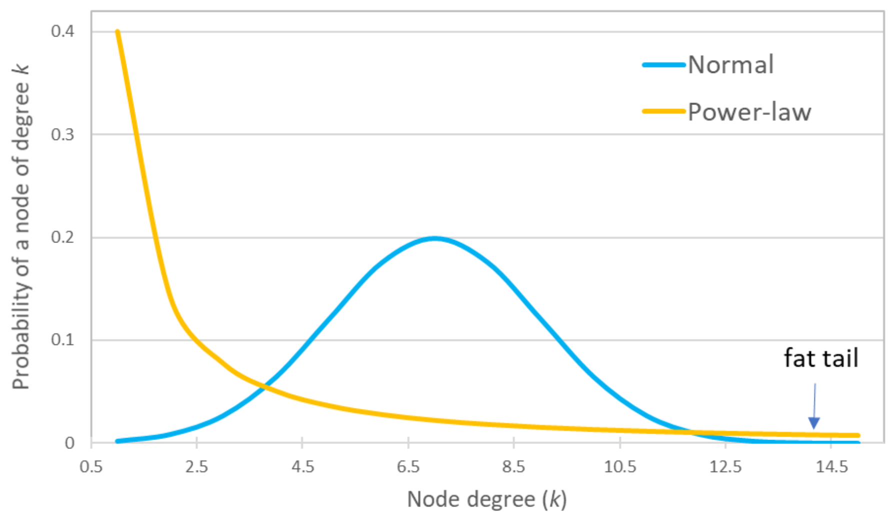

Fig. 2: Degree probability distribution for random graph (normal) and scale-free graph (power-law). In random graphs the nodes are clustered around an average degree and probability for nodes with larger/smaller degree decreases exponentially. In scale-free graphs there are a very large number of nodes with small degree but there are also a few nodes with very high degrees.

The scale free distribution was introduced in economics by Vilfredo Pareto in 1896 (Pareto 1896). The *Pareto distribution* describes very well a number of economic processes, such as the distribution of wealth in the society. It is popularly known as the 80:20 distribution after Pareto's finding that 20% of the people own 80% of the land which follows from the cumulative Pareto distribution. For this reason, it is also referred to as the "rich-getricher" (Gladwell 2008) or "Matthew" effect (Merton 1968). A number of processes have been proposed to lead to a scale-free network/distribution, the most famous of which is *preferential attachment* (Barabási 2016). The network grows through the addition of new nodes linking to nodes already present in the system. There is higher probability to preferentially link to a node with a large number of connections. This rule gives more preferences to those vertices that have larger degrees.

- *Hierarchical networks*

Hierarchical networks are part of the scale-free model family sharing their main property of having proportionally more hubs among the nodes than by random generation. However, it significantly differs from the other similar models in the distribution of the nodes' clustering coefficients: as other models would predict a constant clustering coefficient as the function of the degree of the node, in hierarchical models, nodes with more links are expected to have a lower clustering coefficient. In other words, the local clustering coefficient is proportional to a power of the node degree $C(k) = k^{\alpha}$ where α is called the hierarchy coefficient. Hierarchical network models are usually derived in an iterative way by replicating the initial cluster of the network according to a certain rule (Chung et al. 2003). Thus, the structure of the hierarchical network resembles clusters of clusters.

Network science is now a major field of study. Many systems of huge importance have been shown to exhibit scale-free hierarchical properties, such as gene interactions in the genome and words in natural language taxonomies. Therefore, it is natural to assume that the structure of scientific knowledge follows the same pattern. Here we will use *hierarchical graphs as a convenient representation of a worldview*.

(b) The blind watchmaker

Charles Darwin's theory of evolution (Darwin 1859) is arguably one of the greatest revolutions in thought, probably at par with the Newtonian. The original purpose of the theory was to explain the large variety of plant and animal species; however, its significance has far exceeded the confines of biology. *Evolution is the only known process that can spontaneously construct complexity starting from simple elements*, hence, it was impossible to resist choosing Richard Dawkins' beautiful metaphor for the title of this section (Dawkins 1986). Nowadays, the theory of evolution is an abstract mathematical theory of which genetic evolution is a particular case. In the words of Martin Nowak "whenever information reproduces, there is evolution" (Nowak 2006, p.IX). From this perspective the genetic code is only a particular type of information carrier.

The *basic principles of evolution are replication, variation, and selection* (Nowak 2006). In Darwin's version, evolution via natural selection leads to better adaptation of the species and higher reproductive fitness. The variation was thought to be provided by random point mutations of the genetic code (Schrödinger 1944). However, it was recognized that the speed of point mutations is not large enough to account for the observed variety. This prompted Ohno to propose gene duplication as the leading mechanism for mutation and hence evolution (Ohno 1970). In fact, the gene replication process allows for other types of copying errors in addition to duplication and point mutations such as translocation, inversion, deletion, short indels, etc.

The mathematization of the theory of evolution was helped to a great extent by the development of game theory. Game theory studies the state of systems of agents that interact according to a given set of rules or strategies while trying to maximize certain parameter, referred to as utility in economics and fitness in biology. John Nash showed that in such a game there exists an equilibrium which is defined as a state in which none of the agents can gain an advantage by deviating from his strategy (Nash 1950). In an equilibrium, the majority of the population acts according to the same strategy, which provides the maximum utility for a given amount of effort under the circumstances. The ideas of game theory are extremely well suited for the study of population dynamics. Evolutionary game theory was introduced in biology and applied to study evolution and population dynamics by John Maynard Smith (Maynard Smith 1982).

The process of biological evolution has been generalized to any form of information replication (Nowak 2006). In the general case, "mutations are caused by errors in information transfer, resulting in different types of messages". Then "selection among types emerges when some messages reproduce faster than others" (*ibid*. p.IX). From this vantage point the genetic code is just a particular type of information carrier.

The case of evolution of ideas has been proposed by Richard Dawkins in the *Selfish Gene* (Dawkins 1976). By analogy with the replication unit of the genetic code, he introduced the neologism *meme* as "a unit of cultural transmission, or a unit of imitation" (*ibid*. p.192). The mechanism is that ideas that give competitive advantage are imitated and propagate through the population. Similar ideas have been proposed in economics by Friedrich Hayek in the *Road to Serfdom* (Hayek 1944). He argues that freedom enables individuals to perform "experiments of living" and arrive at novel behaviors. These behaviors, when successful are imitated by other individuals and the whole population moves to another equilibrium point. Thus, freedom to experiment, Hayek argues, powers economic growth.

(c) Prospects

Finally, we turn to the question of rational decision making. Imitating a behavior which is demonstrated to give a competitive advantage is the simplest kind of selection, which we can be labelled *risk-free selection*. However, when new, experimental behaviors arise, generally, there is not yet compelling evidence that they bestow competitive advantage. Thus, risk-free selection does not explain how experimental behavior spreads in the population.

The utility theory in economics deals with decisions under uncertainty and multiple outcomes. Modern utility theory started with the work of the physicist Daniel Bernoulli in a paper entitled "*Exposition of a new theory of the measurement of risk*" (Bernoulli 1954). The assumption is that individuals make estimates of the probabilities p_i of certain outcomes x_i. Each individual has a subjective utility function $u(x_i)$ which measures the utility he derives from a particular outcome. Then the individual's expected utility is the expected value of the outcome $E(\boldsymbol{x}) = \sum_i p_i u(x_i)$. In other words, the utility is a function that maps an arbitrary vector of possible outcomes on a real number $u: \boldsymbol{X} \to \mathbb{R}$. An example of a possible utility function is shown in Fig. 3a. Bernoulli also showed that the utility function is non-linear. For each particular good x, the utility is strictly increasing function, however with a decreasing slope. This shape of the function accounts for the phenomenon of decreasing marginal utility, i.e. the utility of the next unit earned is less than the utility of the previous unit earned. The marginal utility is illustrated in Fig. 3a. For the same increase in x, the change of utility decreases $\Delta u_1 > \Delta u_2$. For example, the utility of $100 is much greater for a low-income person, than for a wealthy person.

The utility function allows for outcomes to be compared and respectively ordered. John von Neumann and Oskar Morgenstern showed what properties the utility function must have in order to make the choice rational (von Neumann, Morgenstern, and Rubinstein 1944). These properties are *completeness, transitivity, continuity, and independence*. In particular, completeness means that any two outcomes can be compared. Transitivity means that there cannot be circular preference i.e. if *A* is preferred to be and *B* is preferred to *C*, then *A* is preferred to *C*. These properties ensure a strict ordering of all possible outcomes. If the utility function has these properties, then the rational choice is to elect the set of outcomes with the highest expected utility. Von Neumann and Mortengstern postulated that *rational agents act as to maximize their utility* (*ibid.*). In fact, *utility maximization* is the basic principle of economic theory (Mas-Colell et al. 1995). In biology it is presumed that utility is directly related to evolutionary (reproductive) fitness, i.e. the ability to survive and procreate more rapidly that the competing species or groups. Thus, the main principle of evolutionary game theory and population dynamics is *maximizing fitness* (Maynard Smith 1982).

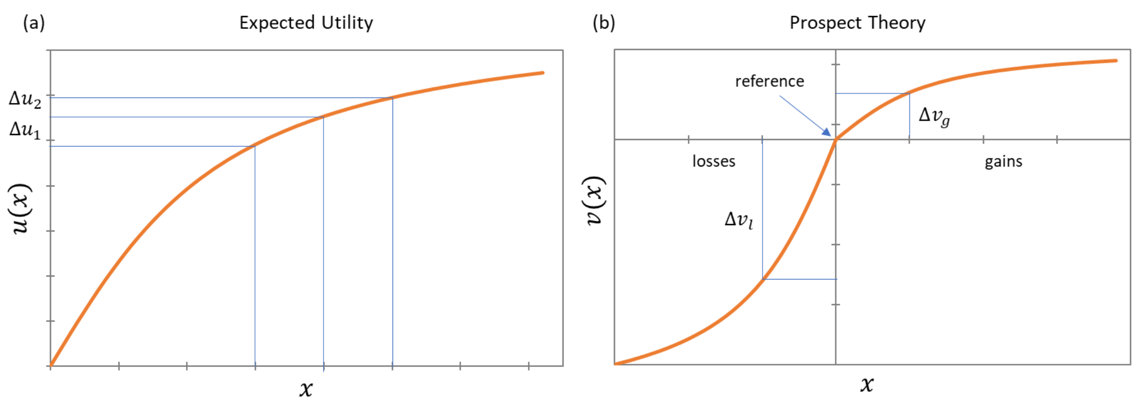

Fig. 3: Decisions under uncertainty: (a) Expected utility function for a single good. It is strictly increasing with diminishing slope (diminishing returns) and (b) Prospect theory utility function. Utility is not absolute but centered around a reference point. It exhibits stronger reaction to losses than gains.

Prospect theory is a further development of utility theory which accounts for certain cognitive processes (Kahneman and Tversky 1979). In this case agents also maximize utility however the expected utility is again given by the expected value $E(\boldsymbol{x}) = \sum_i \pi(p_i)v(x_i)$ but both the probability and utility functions are modified. The prospect theory utility function is illustrated in Fig. 3b. According to prospect theory, the utility is not absolute, but has as a reference point the individual's expectations. Outcomes that are above expectations are perceived as gains and below expectations as losses. The reaction to losses is much stronger than the reaction to gains. This is illustrated in Fig. 3b. For the same amount of loss/gain the change of utility is much larges for the loss $\Delta v_l > \Delta v_g$. In addition, the probabilities are not the objective probabilities, but the perceived probabilities which takes into account certain cognitive biases especially when the probabilities are very low or very high (*ibid.*).

2. Evolution of worldviews

From this point of view, we can explore the hypothesis that Kuhn's theory of *scientific revolutions can be interpreted as evolution of worldviews*.

We can argue that Kuhn's own thinking was developing in this direction. He makes the analogy between scientific progress and evolution in the last chapter of the *Structure*. Kuhn points out that traditional definitions of science and scientific progress fail. The only process that can describe scientific development is evolution "from primitive beginnings but toward no goal" (Kuhn 1962, p.172). Kuhn writes that the "net result of a sequence of such revolutionary selections, separated by periods of normal research, is the wonderfully adapted set of instruments we call modem scientific knowledge. Successive stages in that developmental process are marked by an increase in articulation and specialization" (*ibid*.

p.172). He revisits this topic in the *Reflections*, where he states that his "view of scientific development is fundamentally evolutionary" (Kuhn 1970, p.264). The selection process based on how good they are in solving the problems faced by the scientists, i.e. the predictive power of the theory.

Kuhn's returns again to the "parallel between Darwinian evolution and the evolution of knowledge" in the *Road since Structure* (Kuhn 2000b, p.97), which was meant to be the continuation of the *Structure*, but it was never completed as a book. In this work Kuhn makes the analogy between scientific revolutions and speciation in biology. He also claims that the population that undergoes evolution is the scientific community, an idea he develops in some depth. Kuhn summarizes his position as "post-Darwinian Kantianism" meaning that as "the Kantian categories, the lexicon supplies preconditions of possible experience. But lexical categories, unlike their Kantian categories, can and do change, both with time and with the passage from one community to another" (*ibid*. p104).

Based on these observations, it can be argued that Kuhn's understanding of scientific development tended towards an evolutionary process responsible for the paradigm changes. However, the parallels that he established remained fairly rudimentary for a couple of reasons: first, he spent a great amount of effort defending his ideas against the critique on behalf of the traditional philosophers of science, and second, he did not have the benefit of the modern developments in complex systems and evolutionary theory to base his argument upon.

It is worth mentioning that following Kuhn various authors attempted to establish a parallel between scientific development and the theory of evolution with varying degree of success (Bradie and Harms 2017). Popper himself made a rather contrived attempt to reconcile his view that the growth of knowledge proceeds "by means of conjectures and refutations" with the idea of "natural selection of hypotheses" in the *Objective Knowledge* (Popper 1972, p.261). According to him "scientific criticism often makes our theories perish in our stead, eliminating our mistaken beliefs before such beliefs lead to our own elimination" (*ibid.* p.261) suggesting that the actual drive to do science is evolutionary fitness. Toulmin, elaborating on his criticism of Kuhn's catastrophic picture of scientific development (Toulmin 1970), worked out an evolutionary model of scientific development in terms of "populations of concepts" (Toulmin 1972). He proposed that biological, social, and conceptual evolution are all governed by the same mechanism of replication, variation, and selection. Later authors, elaborated further on these ideas. Donald Campbell coined the term "evolutionary epistemology" to designate attempts to study conceptual change based on models drawn from evolutionary biology (Campbell 1974). David Hull gave a picture of science as a process of "conceptual replication" where reason is involved in the selection (Hull 1988).

In this section we will extend and elaborate the evolutionary parallel by reinterpreting Kuhn's ideas in the language of network science and evolution.

(a) Paradigm as a network of concepts

The notion that the paradigm is a sort of a network has been proposed by Kuhn and others.[†] In response to critique that the definition of a paradigm in the *Structure* is too vague, in the *Reflections* Kuhn developed the analogy between paradigms and lexical taxonomies. The taxonomy is essentially a network of concepts in which the words (or concepts) stand in well-defined relations with each other. Taxonomies differ leading to untranslatability or incommensurability. Incommensurability is the result of incomplete mapping between two taxonomies.

It can be argued that what Kuhn meant by the taxonomy analogy is a network of related concepts or memes. In particular, it has been shown that language, i.e. the words and the connections between them as defined by the synonyms, can be represented by a hierarchical network (Ravasz and Barabási 2003). The natural representation of such a network is the mathematical structure of a *graph* (Barabási 2016). *If the nodes of a graph represent concepts and the edges the relations between the concepts, then this graph is an abstract representation of a paradigm*. Each paradigm consists of concepts or memes and connections between them. Each meme or a concept is a *type*. Each connection is a *rule* of the way the connected memes appear in experience which are often referred to as *natural laws*. An example of such a representation is given in Fig. 4.

[†] For example, Popper refers to the "tree of knowledge" in *Objective Knowledge* (Popper 1972). However, he uses it like a metaphor and does not elaborate on it. A tree is a particular type of simple graph (Barabási 2016) which does not capture the complex relations between concepts.

Having the graph as an aid to model understanding, we can reformulate and substantially extend Kuhn's ideas.

In the Kuhn's view, the most fundamental memes in the graph are 'intuited' from experience in the sense of Kant (Kant 1781). These are consistent, repeating patterns in experience which when postulated help organize the experience as an ordered stream of the same set of objects. The difference from Kant is that the categories used to intuit from experience are not fixed, but they change with the paradigm.

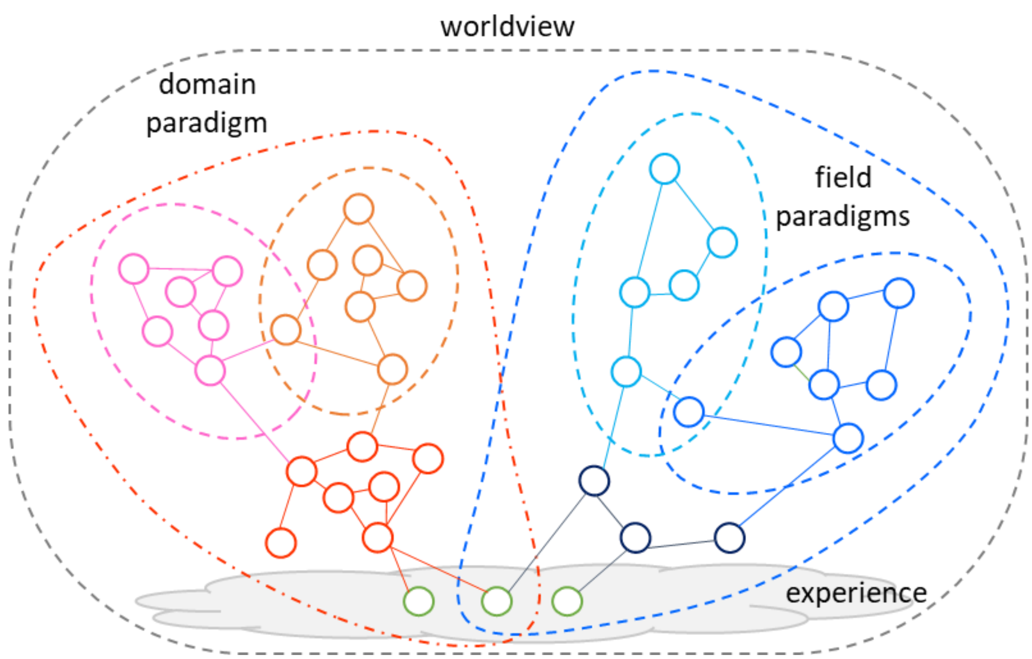

Fig. 4: Graph representation of knowledge as an interconnected network of memes. Circles represent nodes or concepts and solid lines edges or relations. Clustering is indicated by the dashed contours. Hierarchical network consists of clusters of clusters. Each cluster represents a paradigm. Smaller clusters represent field paradigms and larger clusters domain paradigms. The totality of all paradigms is the worldview. The lowest-level memes are in the worldview are intuited from experience.

Kuhn also argued that a paradigm, or in his later terminology a domain matrix, describes a domain of knowledge. However, he did not say anything about the structure of the paradigm beyond that it contains several types of concepts or groups of concepts such as generalizations, values, and exemplars. The assumption that the worldview is a hierarchical network allows us to reveal some additional properties of the paradigm.

- *Levels of abstraction*

Kuhn did state that the paradigm contains both generalizations and particular examples, but he did not explore this distinction. However, as evident from Fig. 4, memes can be of many different levels of abstraction. The foundation of the representation are elementary memes derived from experience. These are consistent, repeating patterns in experience which when postulated help organize the experience as an ordered stream of the same set of objects. The part of the facility of reason, which Kant calls intuition (Kant, 2008), groups the experience into these objects and elevates into the consciousness. Kant assumes that the categories used by the intuition to produce the memes form experience are *apriori* i.e. they come before the experience and are function of the structure of the mind. Kuhn argues that the categories themselves are paradigm dependent i.e. intuition uses the concepts in the paradigm to process the experience (Kuhn 2000b).

Each complex meme can be represented by some convolution of memes from a lower level of abstraction. The convolution of lower level objects to an object at a higher level of abstraction is of the qualitative type, in the sense that the new object is more than a collection of its parts. They are *qualitatively different* in the sense that have new properties and stand in different relationships with other memes on the same level. These new relations cannot be completely expressed in terms of relations between the components.

For example, atoms are the subject of atomic physics. But when atoms combine to form molecules, the new objects have different properties and are therefore a subject of chemistry. One such property is the dipole moment, atoms do not have dipole moments while molecules have. The appearance of a dipole moment in simple molecules consisting of atoms without dipole moments is the example given by Philip Anderson as an illustration of a qualitative change (Anderson 1972). Thus, the appearance of each level of abstraction can be associated with emergence.

It is also useful to define *low-level memes* as those on which a lot of other memes depend for their meaning, directly or indirectly. In Fig. 4 these are the memes sitting closer to the bottom of the graph. The memes directly mapping on experience are obviously the lowest-level ones. *High-level memes* are towards the top of the graph and they resemble leaves. They depend on many other memes but a few (or zero) other memes depend on them. For example, the model of the atom is a very low-level meme shared by many clusters. It is used in chemistry to explain chemical reactions and in solid-state physics to explain the properties of crystals. At the same time, the concept of an LED screen, for example, is a very high-level meme which depends for its meaning on a whole chain of concepts such as light-emitting diode, diode, pn-junction, semiconductor, solid, atom, electron. The same low-level and high-level nomenclature can be applied to clusters.

- *Scaling*

Kuhn also never properly discussed the scale of the paradigm. In his definition the paradigm is a set of concepts shared by a scientific community. However, the community could comprise all the scientists or a very specialized subfield. Obviously, the scale the size of the paradigm (i.e. shared concepts) is very different in the two cases. Kuhn's later reformulation of the paradigm as a domain matrix implies that the paradigm is local, however, he did not explicitly discuss scaling. To make matters even more confusing, in the *Structure*, Kuhn discussed how the change of the paradigm changes the worldview, but he did not equate paradigm with worldview.

The graph representation allows us to visualize the scale of the paradigms.

Memes form clusters or communities in the sense that the memes in a cluster have more connections between themselves than they have with the outside of the cluster. The boundaries of the clusters are indicated in Fig. 4 by dashed lines around groups of tightly connected memes. Each cluster represents a local paradigm. Larger clusters could contain smaller clusters which in turn contain even smaller clusters. The totality of all paradigms is the global paradigm or worldview. Thus, in the network language, the whole graph (Fig. 4) is the *global paradigm* or what we call a *worldview*. The graph can be subdivided into *clusters*, which make up the *domain paradigms* or models of particular fields of knowledge. The domain paradigms consist of local paradigms and the local paradigms themselves can consist of paradigms around a particular problem.

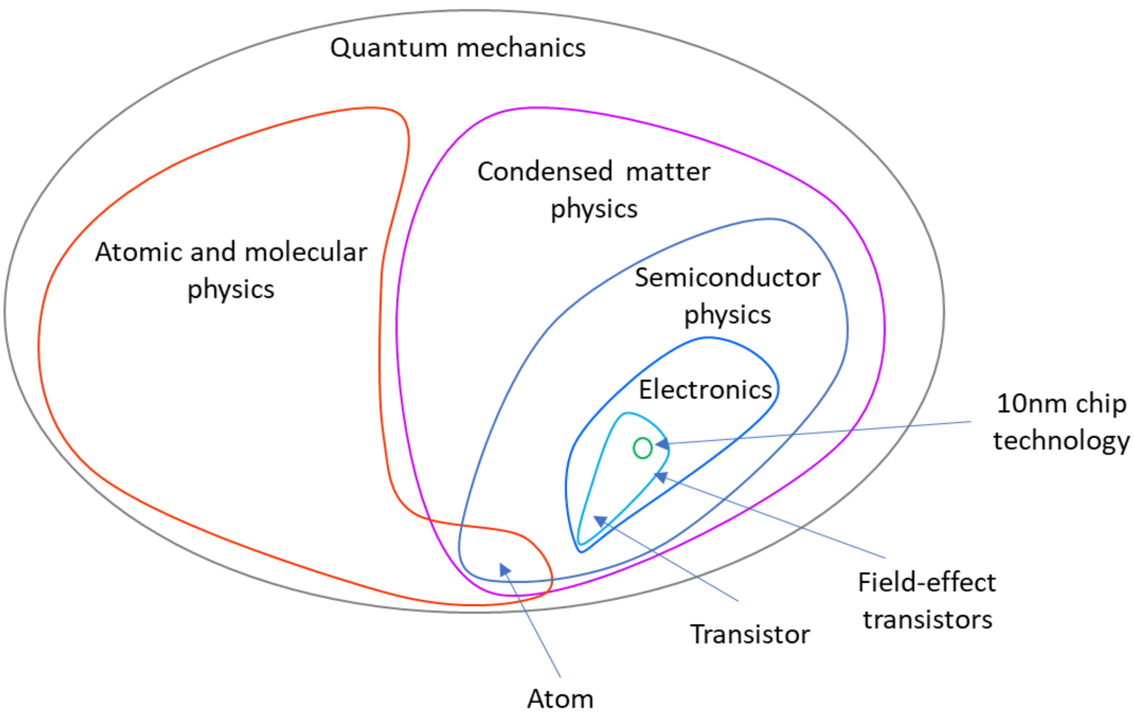

Fig. 5: Rough sketch of the hierarchical structure of quantum mechanics (QM). It contains both atomic and molecular physics (AM) and condensed matter physics (CM). They share some fundamental concepts such as the principles of QM and the model of the atom, however, after that they diverge. CM can further be subdivided in to subfields such as semiconductor physics, which in turn contains electronics, which contains field-effect transistors, etc.

For example, natural sciences is a major cluster in the worldview of which physics is domain cluster. It contains a number of area clusters such as astrophysics, nuclear physics, condensed matter physics, atomic physics, etc. Each of these contain smaller field clusters. For example, a course illustration of the quantum mechanics cluster is illustrated in Fig. 5. Quantum mechanics contains two major fields – atomic and molecular physics and condensed matter physics. In turn, condensed matter physics can be subdivided into crystallography, semiconductors, magnetism, ferroelectricity, etc. These in turn can contain subfields. For example, electronics is a subfield of semiconductors. This hierarchy can be continued further with specializations and sub-specializations. For example, field-effect transistors are part of electronics and high electron mobility transistors are a subspecialty of that. Furthermore, Intel's 10nm technology to lay transistors on a silicon chip is a particular problem cluster within this subspecialty.

Representations

The traditional view is that scientific theories must asymptotically approach reality and therefore they can be compared on the basis of how much closer to the world-in-itself or 'real world' is the new paradigm compared to the incumbent (Popper 1934). Kuhn rejects the notion that we could compare paradigms to the world-in-itself and therefore compare paradigms among themselves (Kuhn 1970). He goes further by stating that there is no evidence that the worldviews created by scientific theories tend to or approach anything. The traditional view corresponds to scientific realism, the main tenet of which is that the world exists independent of any experience. Kuhn's view corresponds to representationalism, however, he did not elaborate on that difference.

The correspondence between reality and scientific theories has passed through several stages. The ancient philosophers did not have the benefit of the modern sciences and therefore subscribed to the intuitive belief that they experienced the real world. In other words, they assumed a 1:1:1 correspondence between the real object, the idea of the object, and the word for the object in the language. Within this picture, it follows that language statements are statements about the *essence of things* and contain truth about the real world. In the classification of Foucault (Foucault 1966), language in this case is the *language of nature*, reflecting the laws of nature. Nevertheless, early on various authors pointed out problems with this correspondence. For example, in the simile of the cave in the *Republic*, Plato can be interpreted that we only have a representation of the real world which is unfaithful (Plato, n.d.). Similarly in *Cratylus*, Plato discusses the second part of the correspondence, between the word and the object, stating the view that words are conventions and do not correspond to the essence of a thing, which also should be evident from the existence of a myriad of languages (Plato, n.d.).

The development of modern science, and in particular, the understanding of the physiology of the sense organs, contributed a great deal to breaking the correspondence between mental picture and real world. It leaves little doubt that our understanding is based on a representation and we do not have direct experience of the real world or the things-in-themselves. Language is a system of signs developed by convention, which is used to convey concepts or states of mind. Again, according to the classification of Foucault (Foucault 1966), language becomes the *language of the mind*, as it reflects the workings or the laws of the mind. Nevertheless, philosophers of science have taken the intermediate stance that although scientific theories are representations, the objects that they describe are real and the theory asymptotically approaches the reality. This is the essence of scientific realism.

The full *linguistic turn* consists in the realization that there is no thought or conceptionalization without language. In other words, a concept cannot exist without being named (Saussure 1916). Thus, reality is just the self-consistent, self-contained, symbolic system of language. The signs within the system point not to reality, but to each other. When new information is incorporated in the system, it is predicated on the existence and structure of the whole system. In this way, understanding the structure of language is the same as understanding reality, and all philosophical questions (and errors) are inherent to the use of language (Wittgenstein 1922).

Thus, it is evident that Kuhn is a proponent of the modern notion of representations of nature. The job of the scientists is to create abstract mathematical models that map on experience. The predictions of the models must agree with empirical evidence. If the model does not agree it is modified or discarded. However, the mapping of models on experience is not unique as there could be multiple models that map equally well on experience. In essence, his view corresponds to the *linguistic turn* in philosophy (Rorty 1970). The scientific realism espoused by the classical philosophers of science can be interpreted as atavism from two ancient notions: first that we have immediate experience of things-in-themselves and second that everything has a purpose (teleology).

Overall, the representation of knowledge as a hierarchical network is not only consistent with Kuhn's definition but it helps clarify to a great extent. It certainly renders the vagueness line of critique mute (Shapere 1964; Masterman 1970).

(b) Normal science

According to Kuhn normal science is the activity of solving problems within the paradigm without challenging the paradigm itself. Knowledge is cumulative, and the progress is fast because there are no arguments about fundamentals. Even though Kuhn set out in the *Structure* to dismantle the preconception of his predecessors that scientific progress is cumulative, his view of normal science is heavily influenced by it. His proposal is to incorporate a period of cumulative expansion in his schema, but to allow for a process to replace the schema. To distinguish the two stages, Kuhn imposed the restriction that normal science does not modify the schema. However, this restriction reduced normal science to a highly technical but routine activity which he himself likened to "puzzle-solving". Toulmin called this view "catastrophism" and pointed out that in fact the distinction between normal and revolutionary science is only one "of degree" (Toulmin 1970, p.41). Although we cannot deny that there is a qualitative difference between normal and revolutionary science, the concept of normal science is clearly lacking.

The graph representation of the paradigm helps to better define and situate Kuhn's concept of normal science with respect to other scientific activity. We start with the proposition that *all knowledge acquisition can be represented as operations on the graph*. What is necessary is to delineate different sets of operations and map them on Kuhn's terminology.

Intuition processes the sensory data from experience in the context of the existing worldview. The result is a mapping of the experience on a type, or in other words, a *phenomenon is an instance of a type*. Thus, intuition can never produce anything intelligible which is outside of the existing worldview. It maps the experience on the closest type. This explains errors of confirmation bias that Kuhn cited in the *Structure*, such as not noticing the wrong color of a suit. A black 2 of hearts does not exist in the worldview, so the intuition does its best to map it and produces an instance of a red 2 of hearts. If the experience is too far from any type it is simply unintelligible.

Eventually, if a particular experience is persistent a new candidate-meme or proto-meme will be formed for the experience to be mapped upon. If the proto-meme is consistent with the worldview, it will eventually be incorporated into it by either mapping it on an existent meme (e.g. the morning and the evening star on the planet Venus); explaining it and decomposing it to a combination of other memes (reduction); or incorporating it into the paradigm as a new node and making the necessary connections to the other memes (discovery).

Thus, normal science, in the language of the graph, can be defined as an activity which produces changes *consistent with the graph*, such as is shifting around of the nodes and redefining their connections (i.e. clarifying and elaborating the concepts and the relations), making new connections in the graph (i.e. discovering new relations), or adding new nodes to the graph in a coherent fashion (i.e. discovering new phenomena). The modifications are performed on an existing cluster.

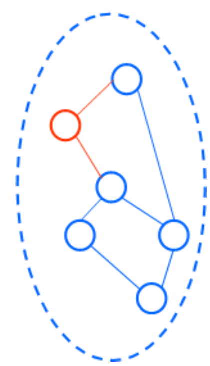

Fig. 6: Graph representation of normal science Normal science adds nodes and/or connections (red circle and lines) to an existing cluster of the graph.

This process is illustrated in Fig. 6 where a new node and couple of edges (in red) are added to an existing cluster (in blue). In other words, *normal science is a coherent expansion of an existing cluster in the graph*. In that sense the activity under normal science is cumulative, because the new knowledge strictly adds to the graph.

This definition solves many of the problems with Kuhn's notion of normal science. First, it is not a trivial activity. Explanation and discovery of new phenomena and laws is part of the normal science activity. Second, not all work under normal science is equal in importance, because it can add any number of nodes/connections and they can be of varying importance due to the hierarchical structure. For example, adding a node to a high-level, peripheral cluster (most embedded clusters, closer to the top of Fig. 4) is of relatively little importance because very few other clusters/memes depend on it. Conversely adding a node/connection to a low-level, fundamental cluster (clusters closer to the bottom of Fig. 4) has large impact because all sub-clusters depend on it. Third, it becomes clear where lies the demarcation line between science and non-science. If a work does not make any modifications to the graph, it is not science. In other words, if the work is derivative, simply revisiting existing concepts and connections, it is not science.

At the same time, it becomes evident that under this definition "puzzle-solving" is certainly not science. However, it could be argued that the problem here is in the definition of a paradigm in that context. As Kuhn himself admitted, he used the word in different contexts to mean a number of related concepts. It could be argued that in the case of normal science Kuhn thought of the paradigm as consisting only of the set of generalizations or axioms. The particular results from applying these generalizations he did not consider a part of the paradigm. This definition resembles Lakatos' distinction between the "hard core" of a theory and its "protective belt" (Lakatos 1970). Indeed, research under normal science does not affect the core of the theory but it adds to its belt. In this sense, in Euclidian geometry the axioms of the theory would be the paradigm or the hard core and all the rest of the results of geometry would be a puzzle-solving activity which adds to geometry's protective belt. Within this interpretation, Kuhn's notion of normal science can be rescued. The confusion comes from the fact that in other contexts, when he defines a paradigm as the set of shared concepts in a scientific community and compares it with a worldview, he seems to imply that is contains not only the fundamental assumptions but also the complete set of results and related knowledge. And frankly, Kuhn's unfortunate choice of words invites the critique.

(c) Anomalies

Kuhn argues that what triggers paradigm changes are anomalies that cannot be explained within the paradigm. In order to define a contradiction and an anomaly in the graph language we need to first discuss the notion of truth on the graph. Kuhn did not discuss truth in the *Structure* beyond the rejection of the idea of absolute truth. In the *Road since Structure* he returns briefly to the subject, giving an account consistent with the linguistic turn picture. He maintains that truth is lexically dependent, i.e. paradigm dependent. Language is a game of coherence, a game with a non-contradiction rule. Fundamentally, *A* and not *A* cannot be claimed at the same time, otherwise the game breaks down. Thus, *truth is making non-contradictory statements within the taxonomy of the language*.

These ideas have a straightforward translation into the graph language. If a new piece of knowledge can be coherently embedded in the existing network by adding connections to existing nodes, then it is normal science. Problems arise when attempts to make connections cause contradictions within the graph, i.e. embedding the new node and edges causes logically contradictory or non-sensical statements.

What is truth in the context of a network? Within the network, a statement contains one or more concepts, their properties, and/or relationship between them. A statement could be false for a variety of reasons. First, the concepts may not be part of the network. Such statements are simple incommensurate with the network and therefore incomprehensible. A weak version of that is the communication between different cultures or subcultures or between disciplines of knowledge. Second, some of the properties may not belong to the concepts. For example, wrong facts about objects or events. Third, the stated connections between the concepts may not exist in the network. The connection can be direct, such as if a species belongs to a class, that is represented by a particular edge in the graph. Checking for such connections is straightforward. However, the connection could also be indirect, involving many intermediate concepts and relationships between them, and may take many logical steps to demonstrate.

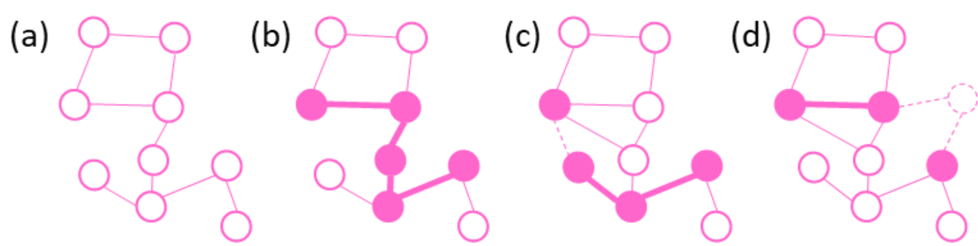

Fig. 7: Valid and invalid statements on a graph: (a) Graph structure. (b) Valid statement as a path on the graph. (c) Invalid statement, non-existent edge (relation); (d) Invalid statement, non-existent node (concept).

Overall, *a valid statement could be represented with a path on the network*, while an invalid statement cannot. An invalid statement, on the contrary, is inconsistent with the network. Either parts of it, nodes or edges, cannot be mapped on the network. Then, a *true statement is merely a valid statement that does not produce logical contradictions*. Valid and invalid statements on a graph are illustrated in Fig. 7. From this definition is becomes clear that *on an internally consistent graph untrue statements cannot be made*, i.e. there are no paths that produce contradictions. Truth is judged when a statement is made and it is mapped on the graph. If the statement is found to be valid (i.e. corresponds to a path on the graph) it is judged to be true. Conversely, if no mapping can be found, then it is judged to be false. Incorrect statements would imply nodes or connections that do not exist on the graph. This definition explains a number of practical phenomena, such as creationism and flat-earth beliefs. Statements about the creation of the world by a bearded man about six thousand years ago are inconsistent with the knowledge network of a scientifically-minded person and it is judged to be false. The same statement, however, is consistent with the knowledge network of a religious person and it is judged to be true.

Using this definition of the truth on the graph we can define an anomaly as the addition of a node and connections that break the internal consistency of the graph or enable contradictory statements to be made. An example of the appearance of an anomaly in a graph is illustrated in Fig. 8. Initially, on the graph two different independent statements can be made leading to X and $\neg X$ (not X) respectively (Fig. 8a). If a new observation appears that connects the two nodes of the statements as illustrated in Fig. 8b, then two contradictory statements can be made starting from the same node A implying X and $\neg X$ at the same time. An example case is that of the particle-wave dualism: a beam of electrons causes a diffraction pattern, like a wave would; but if the electron is a wave, it should not propagate on a straight line like a particle. Thus, the electron can neither be incorporated in the classical mechanics paradigm not in the wave mechanics paradigm, it is a genuine anomaly. To remove the contradiction requires other relations and nodes to be invalidated. In this case we have a genuine anomaly.

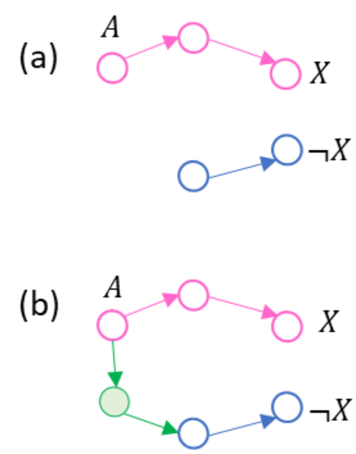

Fig. 8: Illustration of anomaly. The appearance of an anomaly (green node and edges) makes possible for contradictory statements to be made on the graph.

The appearance of a recognized anomalies is what Kuhn calls *a crisis*. The crisis does not automatically invalidate the paradigm. If we accept that the paradigm is not valid, we cannot make predictions. But if we stick with the paradigm, then our criterion of truth fails i.e. there will be contradictory statements in the network. This situation causes the scientists to lose faith in the paradigm. Thus, *crisis is caused of the necessity to operate on an internally inconsistent graph*.

(d) Revolutionary vs extraordinary science

Fig. 9: Graph representation of revolutionary/ extraordinary science. Revolutionary science invalidates clusters (grayed cluster) and extraordinary science adds new clusters (orange cluster in the place of the grayed one).

The appearance of anomalies, i.e. memes incompatible with the graph's structure, causes the graph to be revised. However, due to the interconnectedness of the graph, the revision is very difficult, which is the reason of conservatism and resistance to change. To accommodate the anomaly some neighborhood of memes in the graph must be invalidated and redefined in order to recover the internal consistency of the graph. However, their connection to other memes may necessitate that larger and larger portions of the graph, i.e. whole clusters, to be invalidated. Eventually the graph can be separated in sub-graphs: invalidated memes, valid memes, and demarcation memes at the border between clusters where the invalidation stops. The demarcation memes serve as a boundary condition for the cluster that is to replace the invalidated one. The new cluster should make similar connections to the demarcation memes.

This process is shown in Fig. 9. Attempts to add a node to the grayed cluster results in a contradiction. Because the nodes in the cluster are strongly connected among themselves, the invalidation cannot stop at a single node, it can only stop at the edge of the cluster. Thus, the anomaly causes the whole cluster to be invalidated. In principle, because of the hierarchical structure, the invalidation could expand easily down the hierarchy. An invalidation of a low-level cluster is likely to invalidate all its sub-clusters. A good example would be the recent report of neutrinos moving faster than the speed of light. If this had turned out to be correct, it would have invalidated all relativistic physics. At the same time, an anomaly in a peripheral cluster or high-level cluster is likely to be limit the invalidation to the bounds of the cluster. Although in certain cases, the invalidation can propagate up to the cluster un in the hierarchy containing the invalidated cluster, depending on the strength of the connections and the type of anomaly.

However, cluster invalidation is only one side of the process. The cluster cannot be abandoned until there is a viable alternative to replace it. Kuhn says that the loss of faith in the paradigm frees scientists to try different options. This is the period of extraordinary science when multiple proto-paradigms can exist and vie for dominance. In the language of the graph, a cluster is invalidated and the void in the graph must be filled with another set of memes. The only constraints to the creativity of that process is that the boundary conditions have to be matched and the empirical base to be covered. In other words, connections with the valid portions of the graph have to be preserved. And the phenomena related to experience, including the anomalies, have to be incorporated in the new cluster. The process is also illustrated in Fig. 9. After the cluster is invalidated (grayed cluster), a new cluster, consisting of different nodes and connections, *takes its* *place in relation to other clusters* (orange cluster). However, it is not necessary that the new cluster shares any nodes with the old one.

In principle, there can be many incompatible clusters which satisfy the constraints that the new cluster has to fit in the area of the graph occupied by the old cluster (i.e. make the same connections with the boundary nodes and cover the same empirical base). In this sense the paradigm is not unique. The first paradigm which satisfies the constraints would likely be adopted. This is what in biology is called *frozen accident* meaning that the process of the development of the genetic code was a random, highly improbable combination of events, but once it was developed and it was successful it prevented alternative solutions to develop (Crick 1968). Similarly, the process at arriving at a new paradigm is largely accidental, but once there is a working paradigm there is no incentive to replace it with an equivalent alternative paradigm.

In the beginning the new cluster is smaller and less developed than the cluster it replaces. Therefore, the new paradigm has less explanatory power and less empirical justification than the previous. For that reason, Kuhn argues that objective criteria for choosing paradigms, such as the number of problems resolved or better quantitative agreement with experiment, are not sufficient to pick the new paradigm over the previous (Kuhn 1977b). At this point the personal judgement of the scientist, about the *promise* of the paradigm to resolve more problems, becomes important. One criterion to choose the new cluster over the old is that it incorporates more, or preferably all, of the memes related to experience and perhaps organizes them in a more satisfactory manner. Another, and perhaps a more important, criterion is the potential of the new cluster to make new, previously unthought-of connections i.e. to discover new phenomenology.

Since a cluster cannot be invalidated before there is another cluster to replace it, the two processes go hand in hand. Kuhn himself does not make clear distinction between crisis, revolutionary, and extraordinary science. However, it could be beneficial to separate the different processes because they perform different operations on the graph. *A crisis is properly called the condition when a cluster contains an anomaly and statement on the graph produce contradiction*s. Then *revolutionary science is the process of finding anomalies and invalidating clusters in the worldview*. *Extraordinary science then adds new clusters to the worldview*. According to these definitions revolutionary and extraordinary science strictly remove or add clusters to the graph, respectively. Extraordinary science and normal science are different because extraordinary science adds clusters where previously were none, while normal science only adds nodes to existing clusters. Thus, the *graph representation results in a new classification of the types of science*.

(e) Incommensurability

Within this definition of revolutionary/extraordinary science, namely that a new cluster replaces an invalidated cluster in the graph, leads to a natural definition of incommensurability. If the two clusters do not share any memes (Fig. 9), then there is no standard by which one can be measured against the other. The new cluster can consist entirely of new nodes and edges which is the case of complete incommensurability between the two clusters. However, the incommensurability is limited to this cluster while the rest of the worldview remains the same. Thus, the vast majority of these events lead to local incommensurability. The new cluster can also share some nodes with the old one, but they would stand in different relations with the rest of the nodes, thus their meaning would be modified. A good example of that is the case of the planets, given by Kuhn in the *Copernican Revolution.* The planets remain the same nodes, but they are in a different relation with the Earth, Sun, and the stars in the Copernican and Ptolemaic paradigms, so they are incompatible.

The critique of the idea of incommensurability, is mostly due to the fact that Kuhn's rhetoric in the *Structure* is far-fetched. He talks about an extreme degree of incommensurability, such as the people espousing the two paradigms live in different worlds. This would be true if the whole worldview was invalidated at once, however, this scenario never happens. One of the weaknesses of the *Structure* is that it does not recognize that revolutions can be of very different sizes.

With the help of the graph representation we can see how different scale revolutions can happen and that, in fact, small scale revolutions are common. We recognize that the worldview is not a monolith. Different domain sciences have different paradigms, but also within each science there are sub-domains and within each sub-domain numerous specializations. For example, atomic physics and condensed matter physics are both part of the physics cluster but have almost nothing in common safe for the fact that in both cases the objects of study consist of atoms (Fig. 5).

In the graph language this is visualized as clusters and sub-clusters within larger clusters (Fig. 4). If an anomaly appears in some narrow specialization, it would invalidate some memes within the specialty cluster. However, if these are high-level of abstraction memes which are mostly connected to each other, the invalidation of neighboring memes will stop at the boundaries of the sub-cluster and we will have a small-scale revolution. The discovery of the X-rays is probably a good example of this type of event.

The larger revolutions are caused by anomalies which invalidate some of the more fundamental memes which are connected to a large number of sub-clusters/memes. One such concept was the idea of ether. This was supposed to be the medium which fills all space and propagates the interactions at a distance, such as gravity or electric field. When a fundamental concept like that is invalidated, it could invalidate a large portion of the graph. This is the type of revolution which Kuhn has in mind – that the Earth is not flat, that force acts at a distance, or that humans evolved from apes. In those cases, the graphs and therefore the worldviews before and after are indeed incommensurate.

Thus, the graph representation helps reconcile Kuhn's idea of incommensurability with the arguments of the critics. Large revolutions invalidate a large portion of the worldview and lead to global incommensurability, which is what Kuhn meant in the *Structure*. However, unlike Kuhn's large worldview-scale revolutions, most of the revolutions have only local effect, they invalidate a cluster or a sub-cluster of the graph. With that picture in mind we see that revolutions can be of any scale, depending on the size of the cluster that is invalidated. In fact, because of the hierarchical structure of the graph there are much more small clusters than large ones, therefore, small scale revolutions are much more common. This property makes scale-free networks resilient to large scale changes is due to their hierarchical structure.

(f) Progress through evolution

Kuhn's view of scientific progress, as described in the *Structure*, is a sequence of periods of normal science punctuated with scientific revolutions. The progress during the periods of normal science is continuous and cumulative. These periods are disrupted by revolutions when one paradigm is replaced by another. During the transition the progress is non-cumulative because the much of the work under the old paradigm is discarded as is the work done to develop alternative proto-paradigms. Thus, in the transition there is typically a brief net loss in knowledge. However, this is compensated by the better predictive power of the new paradigm. Kuhn's view of scientific development as normal science interrupted by revolutions is consistent with the *punctuated equilibrium* view of evolution proposed by Gould described earlier (Eldredge and Gould 1972).

Kuhn's later views developed towards the idea that scientific progress is a type of evolution. He announced his new program in the closing pages of the *Structure*, where he compared scientific development with biological evolution. Kuhn says that "the analogy that relates the evolution of organisms to the evolution of scientific ideas can be easily carrier too far. But with respect to the issues in this closing section it is very nearly perfect" (Kuhn 1962, p.172). Kuhn returned to this program in the *Road since Structure* where he attempted "sketch the form" of a "viable evolutionary epistemology" by "returning to the evolutionary analogy introduced in the very last pages of the first edition of Structure, attempting both to clarify it and to push it further" (Kuhn 2000b, p.94).

First, he drew the parallel between the revolutions and speciation – "revolutions, which produce new divisions between fields in scientific development, are much like episodes of speciation in biological evolution". New paradigms develop from old ones, but they are incompatible, like new species that evolve from old ones and become incompatible (i.e. cannot mate and produce offspring). The second parallel was between the units that undergo speciation. In the biological evolution it is the population, "whose members collectively embody the gene pool", is what evolves although the selection is on the level of the individual. Based on this Kuhn speculated that the scientific community, "whose members share a lexicon", is what corresponds to the population of organisms (*ibid*. p.98).

At the end of the *Road since Structure,* Kuhn summarized his stance as a "post-Darwinian Kantianism" (*ibid*. p.104). The Kantianism refers to the way how the paradigm corresponds to the reality, a point to which we will return later. The post-Darwinism refers to the view that the scientific communities evolve very much alike biological species.

It would have been interesting to see how Kuhn's view on the scientific progress would have developed if he dedicated more of his attention to this program instead of fending off critics and if he had the benefit of the modern understanding of evolution. As is, his views remained in this nascent state, but he left the necessary clues. Kuhn is right that revolutions are equivalent to speciation. However, he is wrong that the scientific community is the unit of the evolution. His imagination was shackled by the preconception that it is something physical that evolves, thus he could not make the leap to the idea that the *information itself is what evolves*.

Later authors developed higher levels of abstraction. Toulmin in *Human Understanding* already talks about "populations of concepts change from one time to another on an evolutionary pattern" (Toulmin 1972, p.493) arguing that the same mechanism is responsible for both. He also recognizes that rationality is "concerned far more directly with matters of function and adaptation" than with "formal considerations" (*ibid*. p.VII). Similarly, Hull in *Science as a Process* extends the evolutionary analogy significantly by saying that the "similarity between genetic and memetic replication is enhanced by the apparent appropriateness of talking about the transmission of 'information' in both" (Hull 1988, p.437). He introduces the idea of "conceptual replication" and the mode of scientific progress where the scientific community serves as the medium where this process takes place – "conceptual replication is a matter of information being transmitted largely intact from physical vehicle to physical vehicle" (ibid. p.436).

How should Kuhn's view be restated based on the representation of the worldview by a graph? The hierarchical network model enables us to give not only a better description of the process, but also is conductive to a better demarcation of science. The worldview itself is a hierarchical network of memes. The network evolves by means of three major types of revisions – additions of clusters, expansion of clusters (addition of nodes and connections to an existing cluster), and invalidation of clusters. The process results in a growth of knowledge over time as illustrated in Fig. 10a.

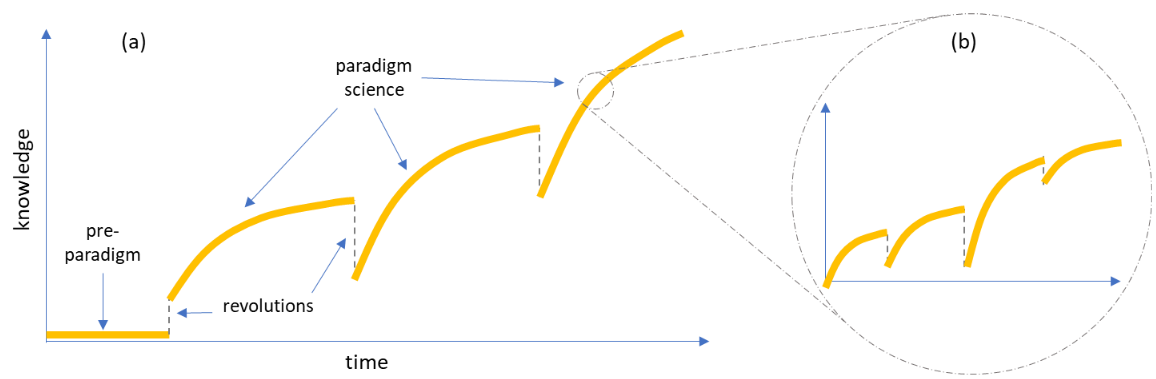

Fig. 10: Scientific progress as expansion of knowledge over time. (a) Punctuated equilibria: periods of normal science (cumulative and continuous) punctuated by revolutions (discontinuous jumps). (b) Scale-free view: a sequence of revolutions at different scales.

Clearly work that does not modify the network in any way is not in the domain of science.

Normal science strictly adds to a particular cluster either nodes (discoveries) and/or connections (laws, relations). The periods of normal science are illustrated by the continuous lines in Fig. 10a. Since concepts/memes and connections are discrete, scientific development is strictly speaking never continuous. Instead it looks like a series of small and large jumps. In addition, science is also not cumulative because cluster of various sizes can be invalidated. Nevertheless, the process of normal science can be illustrated with a *quasi-continuous* line indicating the size of the cluster, because normal science adds individual nodes/connections to the cluster and the change over time is smooth. The line is strictly-increasing because the process is cumulative.

Another feature of the line is its curvature. After a new paradigm is created, the cluster grows very quickly for a variety of reasons. First, there is very large interest in the new paradigm and a lot of work is produced early in the history of the paradigm. Second, the problems scope is known in advance because they are inherited from the previous paradigm. In other words, everything that was resolved under the old paradigm has to be reformulated under the new one. Then, adding to a paradigm early is relatively easy because there are many open problems and the complexity is low. As the paradigm matures, the number of open problems diminishes, and the complexity of these problems increases dramatically. Thus, the rate of development in the beginning is very high which helps the predictive power of the new paradigm to overshoot the old paradigm relatively quickly. However, subsequently the rate of development slows down significantly.

Furthermore, not all normal science is the same in significance. It can differ by the amount of nodes/connections added, but also by their importance. Adding to the higher-level sub-clusters has relatively little importance because few other paradigms depend on it. Adding to lower-level clusters has larger consequences because many other clusters are connected to it, i.e. many other paradigms would be affected.

We can also relate the slope of the line of the normal science development with Lakatos' concept of progressive and degenerating programs. According to Lakatos, a theory is "theoretically progressive" if it has "some excess empirical content over its predecessor", in other words if it makes new predictions that are corroborated (Lakatos 1970, p.118). Otherwise the theory is "degenerating". In his definition science progresses as degenerating theories are superseded by progressive research programs. The problem with this view is that a theory strictly speaking is never becomes degenerating in the sense of Lakatos. Instead the rate of development slows down, i.e. the curve flattens. The reason for this is because research under normal science is extensive, within the dimensions specified of the paradigm or cluster. As the cluster becomes well-elaborated it becomes increasingly difficult to expand it in the pre-existing dimensions. Therefore, such theories are susceptible to replacement by theories which include all the empirical content of the existing theory but also open new dimension for development, thus making the research intensive and correspondingly the dramatically increasing the rate of producing new discoveries.

Overall, the different between the views of Lakatos and Kuhn is that Lakatos believes that the reason for a cluster invalidation is not the appearance of anomalies, as Kuhn claims, but rather that the rate of the development of the theory stagnates. A good example for a transition of Lakatos' kind is the special theory of relativity which included the low-speed classical mechanics as a subset but also opened a new area of research, i.e. enabled the study of the mechanics of objects moving with velocities close to the speed of light. The Newtonian mechanics remains perfectly valid at low speeds, so it can be thought that the Einsteinian version simply extends it enabling the study of a vast array of new phenomena. However, Lakatos' picture completely fails for transitions such as from a geocentric to a heliocentric system. In this case, it was not only that the Ptolemaic system had stagnated, but it was conceptually wrong.

Conversely *extraordinary science adds new clusters* to the network. Extraordinary is represented by a discontinuous jump in knowledge during the transitions between two periods of normal science in Fig. 10a. The jump due to adding a new cluster is always up. However, the new clusters can be in place of invalidated clusters as in the case of a paradigm shift. In that case there is a net drop in explanatory power due to the cluster invalidation that preceded the cluster addition, as in the second and third transition in Fig. 10a. But also, the clusters can be completely new ones, as in the case where no paradigm existed before. In that case the jump is up as illustrated in the first transition in Fig. 10a. Extraordinary science is qualitatively different than normal science because it introduces much larger discontinuous jumps in knowledge than the typical normal science contributions, but more importantly it opens new areas of research and knowledge expansion. In practice it corresponds to establishing new domain sciences which translates into extending predictability over new domains of experience.

At this point we are forced to introduce a new type of science, which is properly called *revolutionary science* the task of which is to *invalidate existing clusters*. The process is represented by the discontinuous drop in knowledge during the transitions in Fig. 10a. It produces new nodes which cannot be incorporated into the existing network, i.e. anomalies, and cause a cluster to be invalidated. This could be a result of conscious effort to test the validity of the paradigm or as an unintended result of the work of normal science. Generally, when a new paradigm is introduced and it is untested, there is a significant portion of the scientific effort is a conscious effort to falsify the paradigm. As the paradigm becomes more established revolutionary science is more likely to occur from accidental discoveries. This behavior is completely rational as the scientists direct their effort to where it would produce the greatest benefit. Chances to topple a paradigm which has withstood hundreds of years of testing are infinitesimal, while the same effort directed towards a new paradigm has much larger probability to result in either revolutionary or extraordinary science.

Finally, the network view enables us to better define scientific revolutions. *A combination of revolutionary and extraordinary science produces a revolution*. Revolutionary science strictly invalidates clusters causing discontinuous dips, while extraordinary science introduces discontinuous jumps. Both these developments are non-cumulative. During a paradigm shift periods many clusters are created and invalidated soon after. Overall during a transition there is a net loss of predictive power because the size of the invalidated cluster initially is larger than the size of the cluster replacing it. Nevertheless, the new paradigm usually spurs the activity in that direction and the predictive power increases very rapidly eclipsing the previous paradigm. A particular case of a revolution is when a domain in a pre-paradigm state and a new cluster is created where no cluster existed before. This also can be though as a revolution where the size of the invalidated cluster is zero. Thus, there is a net jump in knowledge.

Furthermore, the jumps/dips are not of the same size, they depend on the size of the cluster added/invalidated. Extraordinary science and normal science both make small changes to the total size. Even though extraordinary science heralds a large expansion of knowledge its initial contribution has a small effect on the size of the worldview. The subsequent expansion is a product of accelerated normal science. Thus, we can properly call revolutions only the product of revolutionary science, where the effect of the invalidation can be of any size. Due to the structure of the network the distribution of revolutions is bound to have a scale-free distribution. In other words, large revolutions invalidating large portions of the network are rare. At the same time there is very many small-scale revolutions invalidating high-level sub-clusters. And there are revolutions of any scale where the logarithm of the size of the revolution is inversely proportional to the frequency with which it occurs.

Thus, Kuhn's view is completely contained in the evolution of a worldview model. However, the model contains much more information than that. Toulmin argued that the difference between Kuhn's concepts of normal science and extraordinary science is just one of scale (Toulmin 1970). Indeed, the discontinuous events we identified as revolutions in Fig. 10a correspond to the invalidation of large clusters in the worldview. However, between two such large revolutions there could be a number of smaller cluster invalidations corresponding to a discipline or a specialization within a discipline. So, if we zoom the 'continuous' line for a period of normal science we will see the same pattern of coherent growth and invalidations but on a smaller scale, as illustrated in Fig. 10b.

This self-similarity of the curves on different scales is a property of the scale-free distribution. The meaning of 'scale-free' is precisely that if we scale the argument in the distribution it retains its form apart from an overall scaling constant. Thus, if we collect the revolutions of all scales and count them, we expect to observe that (i) there are revolutions of all scales and (ii) there are much more small-scale revolutions than large-scale. If we label with x the portion of the network invalidated i.e. the relative size of the revolutions, then the number of revolutions of this size follow $n(x) = x^{-\beta}$ where β is a positive constant. This is illustrated in Fig. 11 where the number of revolutions of a given size is plotted against the size of the revolution.

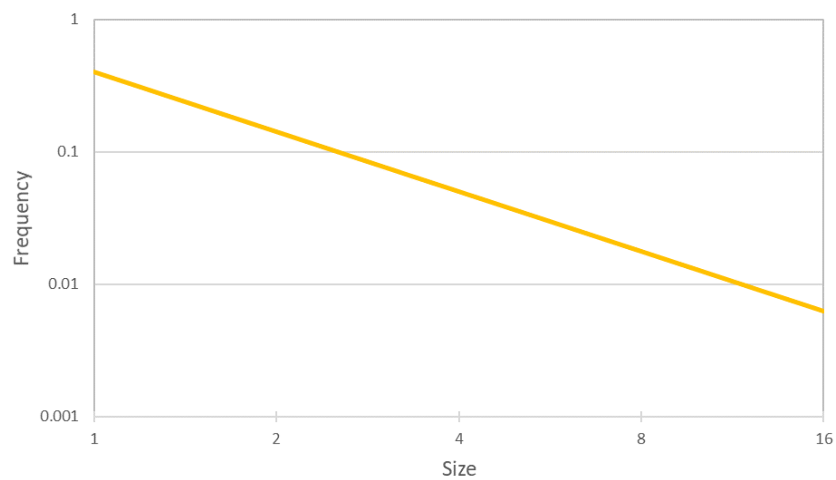

Fig. 11: Number of revolutions vs the revolution size in log-log scale demonstrating the scale-free distribution of the revolutions.

(g) Resolution of revolutions

The picture of scientific progress through revolutions cannot be complete without a detailed account for the dynamics around the transitions from one paradigm to another. Kuhn's account of these transitions, however, met with severe criticism and accusations of relativism and irrationality. The issue of relativism hinges on the relationship between the paradigm and experience and in consequence on the meaning of truth. According to Kuhn, the idea of the truth does not have a meaning outside of the paradigm. True statements are merely consistent with the network, they are paths on the network. Thus, truth cannot be used outside of a paradigm to compare it with other paradigms. Moreover, the network itself is a model of the world that is not unique, there could be many other networks that are consistent with the same experience. Therefore, the paradigm does say anything about things-in-themselves.

After Kuhn rejected the scientific realism doctrine that paradigms are successive approximations of reality and comparison with reality can serve as an inter-paradigm or absolute truth, he had to propose an alternative mechanism for paradigm adoption. In the section of the *Structure* entitled *Resolution of Revolutions* he gives an account of this process (Kuhn 1962).

Once the community has lost faith with the paradigm, scientists feel free to explore alternative paradigms. Eventually a promising paradigm appears, however, in the beginning it is neither more powerful (in the sense of problems resolved) nor more precise (in the sense of quantitative agreement with experiment). It is likely that at its inception the model explains little and could be at par or even inferior to existing models. For that reason Kuhn argues that there are objective reasons to prefer one paradigm over the other, such as that it solves more problems or that it gives better qualitative agreement with experiment, but these reasons are not sufficient (Kuhn 1977b).

Instead Kuhn describes what is essentially a consensus-based mechanism for paradigm adoption. He says that "any new interpretation of nature, whether a discovery or a theory, emerges first in the mind of one or a few individuals" (Kuhn 1962, p.144). Other scientists are then drawn to the paradigm for what Kuhn calls "subjective and aesthetic considerations". The attractiveness of the model is based on "less on past achievement than on future promise" to be compatible with all preexisting knowledge and, in principle, to explain it, in addition to promising to generate new predictions and discover new knowledge. Since there is not sufficient objective basis to choose the new paradigm "decisions of this king can only be made on faith" (*ibid*. p.157,158). Furthermore, Kuhn develops the argument in the *Postscript-1969* that values shared by the scientific community, such as simplicity and coherence, help guide the choice between paradigms during the times of crisis (Kuhn 1962).

This community further develops the paradigm to the point where it advantages become more pronounced. Therefore, more and more scientists adopt the paradigm and gradually the support for the old paradigm dies out, although this frequently requires a generation change because adherents of the old paradigm are too invested in the paradigm to abandon it. The winning paradigm again rally the scientists and usher another period of normal science.

Kuhn says that within this process, the decisions made by the members of the community on each step are rational, and thus not only the whole process is rational, but it is the only process capable of producing a paradigm shift. Scientific progress is means that theories are selected for their predictive power because "one scientific theory is not as good as another for doing what scientists normally do" (Kuhn 1970, p.264). This process does produce improvement of scientific theories, a "gradual but steady emergence of more elaborate, further articulated, and vastly more specialized" with "no goal set either by God or nature" (Kuhn 1962, 172). Kuhn's version of rationality is "fundamentally evolutionary" (Kuhn 1970, 264). It reflects his rejection of the teleology of Popperian philosophers of science, which is nothing more than an atavism inherited from religion.

What Kuhn describes is a fascinating example of population dynamics, quite a bit before the term evolutionary game theory came into prominence. This view can easily be translated into evolutionary language. Essentially Kuhn describes as a cluster of memes propagates in the population. In order to have evolution, first we need a replicator, i.e. an entity that can make copies of itself. In this case the replicator is the worldview, a piece of information represented by the network of memes. The carrier of this information are members of the scientific community. The worldview is *replicated by duplication* in the process of education. Education is realized through formal teaching at schools and colleges, but also through interpersonal interaction and through reading of written sources such as books and papers.

The second requirement for evolution is a mechanism to introduce modifications. This mechanism is a consequence of how individuals process information. In the process of education information is not copied in flat form, instead each person attempts to accommodate each piece of information in his own knowledge network. Thus, the process of education/reading is interpretation rather than copying because there is substantial processing involved. As a result, duplication does not result in identical copies of the network, as should be evident by the very different performance of students in the same class exposed to the same information. The duplication process depends on the initial state of the network as well as on the processing capabilities of the individual. Thus, the network is somewhat modified by each duplication.

In biological evolution modifications are caused by errors in the process of molecular replication. The modern understanding is that rather than random single-point random mutations, errors in copying such as duplication, translocation, inversion, deletion, etc. are much more important mechanisms for producing modifications. Although these processes are also stochastic, they resemble a lot more the process of knowledge acquisition. Ultimately, the nature of the process that produces the modifications is not essential to the argument. The important point is that it produces variants which could have different survival probabilities.

The network is further modified by the conscious work of the scientist in the process of research. There are various modes of research. The scientist could use the network to resolve problems of interest, which is the subject of applied science and engineering. This is science driven by practical needs, which Aristotle referred to as *techne* (Aristotle, n.d.). The scientist could also work on discovering new phenomena and natural laws or on testing the validity of the network and building new frameworks. This is fundamental science, i.e. science without immediate practical aim. Aristotle referred to this type of science as *episteme* and argued that it is due to the love of knowledge and enabled by leisure. Although fundamental science is indeed not possible without leisure, its ultimate purpose is to enable applied science, because applied science is not possible without a framework.

In the process of fundamental research, a cluster is developed in the worldview of a person or a group of people. This modification enables these people to solve successfully some outstanding problems which have long puzzled the community, e.g. anomalies. This demonstrates the promise of the modification to resolve problems. Various members of the community then could imitate (i.e. duplicate) the network with the modification in order to apply it to their own problems. When one worldview replicates faster than the rest, there is selection. If the modified worldview indeed shows utility, then it will propagate and displace the original worldview. If the choice between paradigms cannot be determined by any absolute criterion of truth, simply because such criterion does not exist, then the only possible process that can govern transition between paradigms is the evolution by natural selection. Simply put, better paradigms are the ones with more predictive power that give the communities adopting them a competitive advantage.

The power of the selection process is that it is not necessary for individuals to rationally chose the better worldview in order for the selection to occur. Even if individuals adopt it randomly, the worldview with better predictive power will bestow competitive advantage to those adopting it and improve their reproductive fitness. Thus, provided that the worldview is passed to the offspring, it will spread in the population. Therefore, rational selection is not strictly necessary for the worldview to spread. However, the timescale of this process is generations. This mechanism is identical to the spread of beneficial physical mutations. Beneficial mental processes are selected for just as are beneficial physical traits.

Rationality simply strongly biases the choice in the direction of the better worldview and greatly increases the spread of the modification. To this point we will return in the next section.

Overall, it is clear that Kuhn's theory of scientific progress is consistent with evolution of worldviews. However, Kuhn pursued relatively naïve parallels between biological evolution and evolution of knowledge. He worked too early to be able to adopt the idea, proposed by the likes of Dawkins (Dawkins 1976) and Nowak (Nowak 2006), that information itself evolves. Although the natural selection is on the level of the individual and communities of individuals, it is the worldview as an information structure that evolves and the individuals are carriers of this information structure. This idea was put forward by Dawkins in the case of genes in the *Selfish Gene* (Dawkins 1976). From this perspective it is individual genes that try to propagate themselves as much as possible and the individual is their "survival machine". Hull restates the same idea in *Science as a Process* (Hull 1988), except in the context of memes, by saying that ideas use the individuals as a "physical vehicle".

(h) Emergence of rationality

Finally, we have to elaborate on the role or rationality in paradigm shifts. In other words, why are worldviews selected for their predictive power? In more general terms, this question can be posed as what is behind the proverbial love of knowledge which drives the evolution of worldviews? Kuhn himself closes the *Structure* with this question "why the evolutionary process should work? What must nature, including man, be like in order that science be possible at all?" (Kuhn 1962, p.173).

A possible approach to these issues is to revisit the concept of truth, with which Kuhn struggled to the extent that he did not even mention it in the *Structure*. He only used the concept in the negative, i.e. to say that it is not valid outside of a paradigm. Indeed, the concept of truth in the everyday language is problematic. Consider the statement 'this painting is beautiful'. Is this a true statement? Even if we assume it to be true, we still have to admit that the statements 'this painting is beautiful', 'the Earth revolves around the Sun', and 'two plus two is four' are very different kinds of truths. Part of the problem is that the same word, namely truth, used in different situations means different things. If define it in one context, we can quickly find an example which calls for the same word but in which the definition fails.

For example, there is an abstract truth, as in mathematics and logic, which expresses the conformity of a given statement with a set of abstract objects and the relationships between them. These objects and relationships are not related to perception and simply reflect the way the mind is wired. Thus, a true statement of this kind will always remain true. There is also empirical truth, as in the natural sciences, which expresses the conformity of a statement with empirical facts. The objects derived from experience are just a possible model of the world outside. Statements based on this model are only true as long as the model faithfully maps on reality. However, it can never be known if this is the case and there is always the possibility to obtain empirical evidence which contradicts the truth and invalidates the model. Furthermore, there is the truth as understood in the humanities. There, the number of parameters on which something depends is too large or altogether unknown for a statement to be tested in an experiment. Since it cannot be demonstrated that a statement conforms to empirical evidence, it is assumed true if it produces the desired result most of the time. But there is also truth in probabilistic judgments, such as in investing on the financial markets or in weather forecasting. In this case, a prediction is truthful if we get the desired outcome with a given degree of certainty.

Is there anything that unifies these notions of the truth?

The answer is quite simply evolutionary fitness. Before we elaborate on this notion, it is worth pointing out that ever since Plato elevated philosophy above the mortal and the material, it has largely stayed divorced from the notion that it is but one of the activities of mortal beings of limited capacity. The truth and the love of knowledge are a problem of the immortal gods. The problem of mortal and limited beings is survival. If philosophy in general and truth in particular have no survival value, then they would not be practiced and would have never developed. Nothing the cost of which exceeds its benefits would be selected for.

Truth then must have benefits. To try to understand this, let us consider two animals – one irrational and the other rudimentary rational. During their lifespans both would encounter adverse circumstances to which they would need to react. The irrational animal would react randomly and therefore would make the wrong choices a fraction of the time. This would result in reduction of its fitness. The rational animal, under the same circumstances, would try to model the environment and make a prediction before reacting. No matter how rudimentary the model, even if it is slightly better than a random guess, on average it would result in fewer wrong choices and in smaller reduction in fitness. Thus, the rational animal would have a better chance of survival and higher chance to produce offspring. Rational modeling, therefore, would be selected for and, assuming that the facility of reason is transferred to the offspring, it will spread in the population.

The conclusion is that the value of truth comes from its predictive power. Since, any prediction is better than none even a partial truth, which gives the right results more often than not, is better than no truth. This explains why there are many different criteria of truth and why frequently we are satisfied with very weak ones. That also explains why reason infringes on areas beyond the mathematical and empirical, where the truth cannot unequivocally be tested. We will develop a criterion of truth, every time when even poor predictive modeling yields tangible benefits. Furthermore, belief is better than no knowledge at all. By trusting information from other sources, we greatly expand our predictive power although the criterion of truth is even weaker because the trustfulness of the source must be accounted for.

Reason is the facility that builds models of reality in order to *predict the immediate consequences of certain actions under certain conditions* and choose the most appropriate response from a set of possibilities. From this definition it is obvious that any species with even very rudimentary power to predict the future will have a survival advantage. Reason is nothing but a *tool for survival*. Thus, the development of reason is expedient.

In this line of argument, reason is just an extension of motor instincts. All forms of life have certain instincts to react to certain immediate stimuli. The difference is that the instincts are hard-wired and therefore they develop slowly, over generations. While with reason better and more sophisticated models can be developed over the lifetime of an organism. If we make an analogy with the digital computer, instincts are encoded in the firmware of the computer (permanent, non-programable), while reason is a in the operating memory (programmable). This enables the possibility that paradigms are modified or replaced within the lifetime of the individual, which greatly increases the speed of propagation of successful worldviews.

Given that reason is the facility to construct and use paradigms in order to get competitive advantage, still the question of the choice between paradigms remains. As Kuhn pointed out in the beginning new paradigms do not have more predictive power than the existing paradigm and therefore it does not seem rational to adopt them. For that reason, he proposed that there are psychological and sociological factors that play a role in the adoption. However, he insisted that in the end the new paradigms turn out to have better predictive power and the selection is rational.

There are couple of fallacies with Kuhn's view. First, if paradigms are indeed selected for their predictive power then the choice would be objective as the philosophers of the Popperian tradition claim. However, Kuhn himself contends this notion. Second, Kuhn did not consider failed paradigms. It is not at all true that each paradigm shift is in the direction of better predictive power. Consider, for example, the paradigm shift that culminated with the burning of the Great Library in Alexandria by a Christian mob.

Rather, the decision of paradigm adoption is utility optimization under uncertainty, and it is not immune of errors.

Rational behavior is to optimize utility. Individuals value certain outcomes that improve their wellbeing and evolutionary fitness. Different paradigms modify the probabilities of the various outcomes. Individuals compare paradigms by making guesses about the likelihood of desired outcomes under each paradigm. They adopt the paradigm that is expected to maximize their utility. As long as the probability estimates are better than random, utility maximization will favor the adoption of the better paradigm and it will hasten its spread.

The utility maximization vantage point explains a range of phenomena. Most importantly, it explains why at the inception of a new paradigm, when the paradigm's predictive power is still inferior to that of the incumbent paradigm, it still spreads. Scientists make guesses on the *likelihood* to resolve certain problems and to expand the predictive power of the paradigm beyond that of the existing paradigm. Thus, they make the choice based on this expectation rather than on objective comparison.

The utility view also explains the psychological component in the paradigm selection. Although obtaining a model with better predictive power is the principal desired outcome, the individual's utility function contains a number of other subjective outcomes, such as the scientist's career and wealth. Considerations such as the sink cost (i.e. the amount of work already invested in the old paradigm) and fame (i.e. the possibility to make a name for himself) favor young scientists to adopt the new paradigms and the older scientists to resist them.

Furthermore, the utility optimization accounts for sociological components of paradigm shifts. Scientific developments benefit the group much more than the individual. Therefore, the society makes certain decisions intended to support scientific progress, such as paying taxed to fund education and research and conferring certain prestige and financial reward to certain professions. However, with that society also influences the direction in which researchers work and the desired outcomes.

V. Structure of the Structure

The *Structure* is undoubtedly a revolutionary work. Kuhn essentially broke every tenet of the traditional philosophy of science, a task which was probably facilitated by the fact that as a physicist he was not indoctrinated in them. His originality and the depth of his insight and intuition made the *Structure* a bestseller and thus impossible to ignore. The establishment's only course of action was to defend itself by mounting a critique. This critique exposed many weak points in Kuhn's theory, which however did not diminish its appeal. A reader cannot help but think that Kuhn's ideas are correct in principle if not in detail. And Kuhn left in the text enough clues on where he intended to go next if time and/or co-developments in the scientific milieu allowed him.

In this work we gave a comprehensive review of Kuhn's theory of scientific progress with emphasis on his later evolutionary perspective. However, as Nietzsche points out that "one repays a teacher badly if one always remains nothing but a pupil" (Nietzsche 1883, p.78), we went further to recast Kuhn's theory as an *evolution of worldviews* utilizing recent developments in network science and evolutionary dynamics. This allows us to systematize and clarify Kuhn's view as well as to answer some of the critiques and correct some of the problems with Kuhn's theory. But most importantly it helps to identify an underlying principle behind Kuhn's observations and build a consistent picture of scientific progress as a type of evolution. This picture allows us to go beyond Kuhn and reach even greater generalizations.

A new type of rationality

The faculty of reason is a tool to organize experience and make predictions about the future. In its role it is complementary to memory which serves the same role for the past. This faculty has a clear survival value and therefore it is selected for in the process of evolution. The result of the activity of this faculty – science – is thus an evolutionary adaptation.

Reason performs its function by building models that are mapped on experience. A model that maps on a particular domain is a local paradigm, the totality of all models comprises a worldview (i.e. a global paradigm) There is no thought or conceptionalization without a worldview. Thus, reality is just the self-consistent, self-contained, associative network of concepts or memes. The memes within the network point not to reality, but to each other. When new information is incorporated in the system, it is predicated on the existence and structure of the whole system.

The purpose of building a model is to make predictions. Predictions are statements that can be evaluated on the network. A statement it is a path on the network consisting of nodes (memes) and edges (connections). Truth is making statements consistent with the network. The model could be very course-grained and not map on experience very well. Nevertheless, it is valuable if the makes correct predictions more often than not and on average increases the evolutionary fitness of the individual using it. At the same time there cannot be any such concept outside of a worldview.

Rational behavior is to adopt any model which makes better predictions than the existing models and therefore improves evolutionary fitness. Such decisions are made under uncertainty such as each individual maximizes their own utility bases on expected outcomes under the different paradigms.

A new understanding of scientific progress

A worldview is postulated to be a hierarchical network of concepts or memes. In this model related memes are connected into clusters, related clusters into larger clusters, etc. Each cluster represents a local paradigm. Loosely speaking the smaller clusters correspond to sub-fields of science, larger clusters to domain sciences, even larger clusters to domains of knowledge. The network of all clusters (paradigms) is the worldview.

Scientific progress is evolution of the worldviews. The worldview is an information structure. Worldviews replicate by duplication where individuals serve as carriers. Each individual receives a copy of the worldview in the process of upbringing and education. Variation is introduced by modifications during the replication process. New memes and paradigms are added by incorporating them into a pre-existing network which produces modifications due to different initial conditions and processing ability. Furthermore, targeted modification of the worldview is produced in the process of inquiry and scientific research. Initially modifications exist in the worldviews of individuals or small groups. Inevitably some of these modifications bestow competitive advantage to the individuals or groups subscribing to the worldview. Selection is produced by other individuals and groups adopting the successful worldview in an effort to gain the same advantage. Thus, the modified worldview would duplicate faster than other worldviews, spread, and possibly become dominant. The net effect of this process is more elaborated worldviews with ever increasing predictive power.

A new demarcation of science

The hierarchical network model also yields *a new demarcation of science*. Ultimately the goal of the worldview is to make predictions that map on experience. Paradigms that cannot yield empirical predictions are useless because they do not have evolutionary benefits. Furthermore, *nothing that does not increase the predictive power of the network is science*. Decrease of predictive power is evolutionary disadvantageous and not rational behavior. As a corollary, a cluster of the network (i.e. a paradigm) can only be invalidated if there is a new cluster to replace it.

Finally, we can develop a *new classification of the types of science*. Normal science results in expansion of a single cluster (paradigm). It can add new nodes and/or connections to the cluster corresponding to the discovery of new phenomena and relations. The increase of knowledge is quasi-continuous because the size of the cluster strictly increases in small steps. It is cumulative because normal science strictly adds to the cluster. The importance of work under normal science depends on whether the additions are to a fundamental (low-level) or to a peripheral (high-level) cluster which determines how many other clusters and memes are affected by the addition.

Extraordinary science on the contrary produces new clusters which could be in a place of the network not previously explored or replacement of invalidated clusters. Extraordinarily science also strictly adds to the network, but its contribution is qualitatively different because it not only produces discontinuous jumps in predictive power but also opens new area of research thus enabling predictions over areas of experience previously inaccessible. Conversely revolutionary science strictly removes from the worldview by invalidating paradigms. Due to the structure of the worldview these events, which are aptly called revolutions, follow a scale-free distribution i.e. there are events of any scale, but the number of events of given size is an inverse power law of the event's size. In other words, large revolutions are extremely rare while there is a myriad of small-scale transformative events.

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